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Large Truck Braking at Signalized Intersections

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Large Truck Braking at Signalized Intersections

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Abstract:	Simplified braking models were used to analyse the braking distances, braking efficiencies and traffic signal clearance times for a range of truck types operating at a variety of speeds under different loading conditions on pavements with various skid resistances. These analyses show that the trucks examined could only satisfy existing standards for each of the above performance measures when tire-pavement friction coefficient magnitudes were in the range of 0.5 to 0.8, where the standards are based on a friction coefficient of 0.3. The analyses suggest that the existing standards for signal timing and alignment design should be carefully evaluated in the light of the truck braking capabilities summarized in this report.
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Large Truck Braking at Signalized Intersections

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EXECUTIVE SUMMARY

The inter-phase clearance times at traffic signals and the geometric design of highway alignments are both based on safe stopping sight distance standards. Current standards are derived from the braking capabilities of motor vehicles with perfect braking efficiencies operating on pavements which produce tire-pavement coefficients of friction of about 0.3. This coefficient of friction is typical of worn tires operating on wet pavements with inferior surface characteristics.

Perfect braking efficiency requires that the forces exerted by the brakes on each wheel be proportional to the normal forces transmitted to the pavement through each wheel. The braking force developed at the tire-pavement interface at each wheel is the product of the normal force and the coefficient of tire-pavement friction. Wheel lock-up occurs when the brake torque exceeds the braking torque and wheel lock-up may result in loss of directional control.

Perfect braking efficiency cannot be achieved in trucks at all times because of their fixed brake systems and varying wheel loads. Wheel loads vary with cargo density, loading configuration and deceleration magnitude. Brakes proportioned appropriately for a fully loaded truck may be unsatisfactory for a partially loaded or unloaded condition.

The braking capabilities of a range of truck types operating at various speeds and under a range of loading conditions on pavements with varying skid resistance characteristics are analysed in this report. The trucks analysed include straight two- and three-axled trucks, tractor semi-trailers with and without belly axles and A- and B-train double trailer combinations. The truck types analysed are not peculiar to Ontario and are representative of the set of trucks using the North American highway system. The issues raised about truck braking capabilities in this report are expected to be common to many jurisdictions throughout North America. Three inter-related performance measures are used to reflect truck braking capabilities and these are braking distance, braking efficiency and signal clearance time. These braking performance measures are calculated at the point at which wheel lock-up first occurs and this is equivalent to controlled braking. The analyses use a set of simplified braking models developed at the University of Michigan Transportation Research Institute which have been adapted to the special needs of this project. The mass, dimension and brake system characteristics used in these models have been obtained from a variety of sources.

The analyses demonstrate that none of the truck types evaluated are capable of meeting the current safe stopping sight distance standards for the friction coefficients assumed in these standards and this reflects the less than perfect braking efficiencies of the trucks analysed. The analyses show that braking distances are strongly influenced by cargo density, loading configuration and of course, speed and pavement skid resistance characteristics.

The loaded truck types requiring the longest braking distances included a 3-S2 semi-trailer loaded with low density cargo, an A-train double loaded with medium density cargo and a bobtail tractor. The inferior stopping distance properties of these vehicles are magnified as pavement skid resistance decreases and operating speed increases.

Partial loading tends to exaggerate the inferior braking capabilities of some of the vehicle types, particularly on pavements with low skid resistances. The braking distances required by the 3-S2 tractor semi-trailer and the A- and B-train doubles with rear trailers empty increase sharply.

Tests of unloaded trucks show that their braking distances are shorter than when they are partially loaded but longer than when they are fully loaded. The largest increases over the fully loaded condition are for the vehicle types just mentioned and belly-axled semi-trailers with tridem rear axle groups with their belly axles raised.

Draft inter-provincial truck regulations suggest a minimum truck braking efficiency of 70 percent under a range of loading and operating conditions. Analyses of truck braking efficiencies show that a number of the truck types cannot consistently achieve a braking efficiency of 70 percent under the range of load speed and pavement skid resistance conditions tested. The particularly sensitive vehicles include the 3-S2, the belly-axled semi-trailers with tridem rear axle groups, the double trailers with unloaded rear trailers and the bobtail tractor.

Current standards for inter-phase signal clearance times are based on a deceleration of 0.31 g and this translates into a clearance time of 5-6 seconds depending on vehicle length, intersection width and operating speed. With perfect braking efficiency this means a threshold tire-pavement coefficient of friction of 0.31. The evidence on braking distances and braking efficiencies summarized above indicates that trucks are unable to achieve perfect braking efficiency and the deceleration of 0.31 g can only be achieved by trucks when the coefficients of friction are in the range of 0.5 to 0.6 for most of the truck types and up to 0.8 for some of the double trailer combinations. Skid resistances of this magnitude are only achieved with unworn tires on dry pavements with good surface condition.

A review of several studies of truck accidents in Ontario suggest that the evidence on truck braking capabilities presented in this report is compatible with the accident experience. Unloaded trucks are over-represented in truck accidents and the causes of many of these truck accidents have been traced to the degradation in braking efficiencies of the unloaded trucks.

The evidence on truck braking presented in this report suggests that the current engineering standards used for highway system design should be carefully evaluated. An appropriate response may be to develop modified design standards for highway facilities expected to carry significant volumes of trucks.

CHAPTER 1

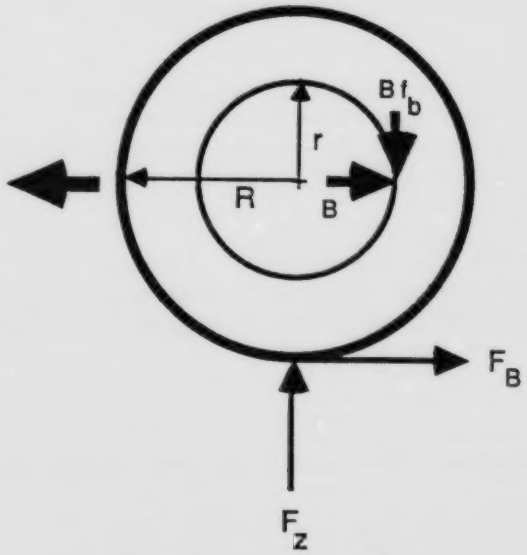
TRUCK BRAKING AND HIGHWAY TRANSPORTATION

1.1 Project Scope

The braking capabilities of trucks have important impacts on several aspects of highway design and management and these include stopping sight distance standards for vertical and horizontal alignment design, and signal timing. For example, signalized intersections allocate the traffic carrying capacity available at an intersection between the conflicting traffic movements. An important decision in signal timing is the time allocated for clearance between the green times assigned to the conflicting traffic movements. The clearance time between phases consists of the amber time plus any all-red signal time. One of the components of an appropriate clearance time is the time required for trucks to brake to a controlled stop once a driver detects an amber signal.

The primary objective of the research project described in this report is to analyze the braking times of a range of large truck designs and to relate these braking capabilities to the *signal clearance times* required for the safe operation of signalized intersections.

Figure 1 shows the forces acting on a tire during braking and these include F_B, the braking force developed at the tire-pavement interface which derives from the product of the normal force F_Z and the tire-pavement coefficient of friction f; F_Z, the normal force transmitted through the tire to the road; B, the actuating force acting through the brake shoes on the brake drum; and B f_b, the brake force developed at the brake lining-brake drum interface which derives from the product of the actuating force and the coefficient of friction between the lining and the drum.



rolling resistance & drag omitted

Figure 1. Forces Acting on Tire During Braking

One case for the braking of the wheel illustrated in Figure 1 is that for which the brake torque ($B\ f_b\ r$) just balances the frictional torque ($F_Z\ f\ R$) developed at the tire-pavement interface. This condition would utilize fully the available road friction.

A second case is that for which $B\ f_b\ r < F_Z\ f\ R$ at maximum brake pedal pressure and this means that a truck would be under-braked for the particular conditions. This might occur for heavily loaded trucks with good tires operating on dry pavements, where the large magnitudes of both F_Z and f would produce high frictional torques that could not be fully mobilized by the brake system of the truck.

A third case is that for which $B\ f_b\ r > F_Z\ f\ R$ and this would produce wheel lock-up. Tires must also provide directional stability where this is developed by the rotation of a tire. If wheel lock-up occurs, then the lateral force required to provide directional stability cannot be developed and a vehicle may deviate from its intended path. Wet or icy pavements decrease f and even a modest application of the brake pedal may produce a brake torque greater than the frictional torque, and therefore, wheel lock-up.

Full mobilization of the tire-pavement friction at each wheel of a multi-axled truck is difficult to achieve under a variety of conditions. Full mobilization (ideal braking) is only achieved when the brake torque and the frictional torque are equal at each wheel. This is impossible to achieve with current braking systems since the load at each wheel varies between the loaded, partially loaded and unloaded conditions. Ideal braking could only be achieved under this range of load conditions if the brake actuating force at each wheel could be adjusted as the wheel loads change. Premature wheel lock-up may occur when the brake forces are not proportional to the normal loads at each wheel and this prevents the available tire-pavement friction from being fully mobilized at the other axles, and braking efficiency would be less than ideal.

On horizontal curves some of the tire-pavement friction is required to develop lateral acceleration on a curve and this reduces the frictional torque available for braking.

A second objective of the research project is to explore the variations in *braking efficiencies* of a range of large truck designs with changes in the load distributions between axles. Braking efficiency may be defined as the ratio of the frictional force utilized by a truck during braking to the frictional force that could be developed under ideal braking.

The braking distances required to stop a truck from a particular operating speed are important inputs to the design criteria used to establish vertical and horizontal curve lengths, as well as in the establishment of appropriate amber clearance times. A third objective of the research project is to estimate the changes in the *braking distances* required to stop vehicles from various operating speeds with changes in load distribution and tire-pavement friction.

The following sections of this chapter explore each of the three objectives in more detail. The braking distances required by trucks to stop from various operating speeds under various loading and pavement conditions are first examined since braking times are required to establish amber clearance times.

1.2 Braking Distances

The braking distances specified in the Canadian geometric design standards (8) are normally calculated from :

[1] $$d_b = \frac{v^2}{2\,g\,f}$$

where d_b = the braking distance (m) ; v = the operating speed (m/s) ; f = the coefficient of tire-pavement friction ; and g = the acceleration due to gravity (m/s^2).

Eqn [1] is derived from the mechanics of braking of a rigid body where issues about load transfer between axles during braking are not considered. Typical values of the braking distances calculated from eqn [1] using the coefficients of friction contained in the RTAC Geometric Design Standards (8) are summarized in Table 1.

Table 1. Braking Distance versus Running Speed

Running Speed (km/h)	Coefficient of Friction	Braking Distance (m)
50	0.36	27
60	0.34	42
80	0.31	81
100	0.30	131

Source : ref (8)

It should be noted from Table 1 that doubling the running speed from 50 km/h to 100 km/h increases the braking distance by 4.8 times.

The safe stopping sight distances used for the design of vertical and horizontal alignments consist of the *braking distance* required for a particular running speed plus the distance travelled during the time (usually assumed to be 2.5 s) required by a driver to perceive of the presence of a hazard and to begin to apply the brake, and this is known as the *brake reaction distance*.

The coefficients of friction used in the geometric design standards to derive braking distances and summarized in Table 1 are based on the following considerations (8):

> *"Braking distance calculation is based on the laws of motion in which it is assumed that the coefficient of longitudinal friction is constant throughout the braking period. Values for the coefficient of friction for minimum stopping sight distance assume conditions approaching the worst, and the values adopted are consistent with tires in poor condition operating on a pavement in poor condition with a wet surface."*

The analyses described in this report are for a range of tire-pavement frictions and Figure 2 summarizes typical ranges for different pavement conditions. The diagram illustrates that there is a wide variation in the coefficient of friction for any pavement condition.

Truck tires typically develop less friction at the tire-pavement interface because of the rubber compounds used to provide better wear under heavy loads. Figure 3 illustrates the coefficients of friction for truck and car tires for a range of speeds and tire tread depths reported by Dijks (9). The diagram illustrates that the coefficients of friction developed by truck tires are substantially lower than those developed by car tires.

Mechanics of Braking

Figure 4 shows the forces acting on a straight three-axle truck at maximum braking effort. These forces consist of the normal forces acting on the front and rear axles, the maximum braking forces that may be developed at each axle (normal force times coefficient of friction). The brakes mobilize the braking force available at the tire-pavement interface by transforming the brake line pressure into a force applied through

the brake lining against the brake drum. The efficiency of this transformation is clearly related to the coefficient of friction that is developed between the brake lining and the brake drum.

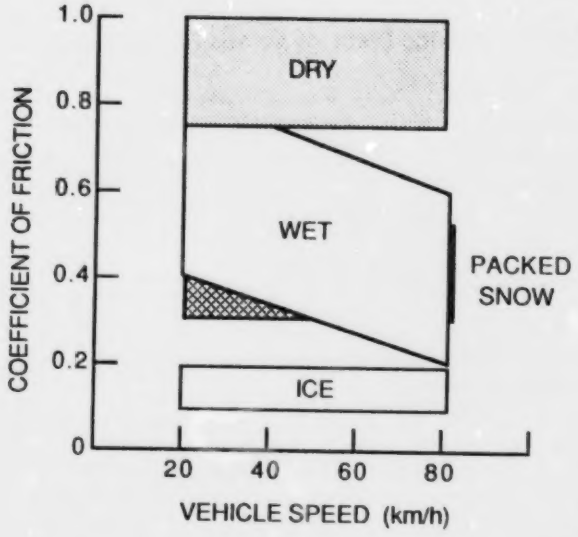


Figure 2. Variation in Coefficient of Tire-Pavement Friction

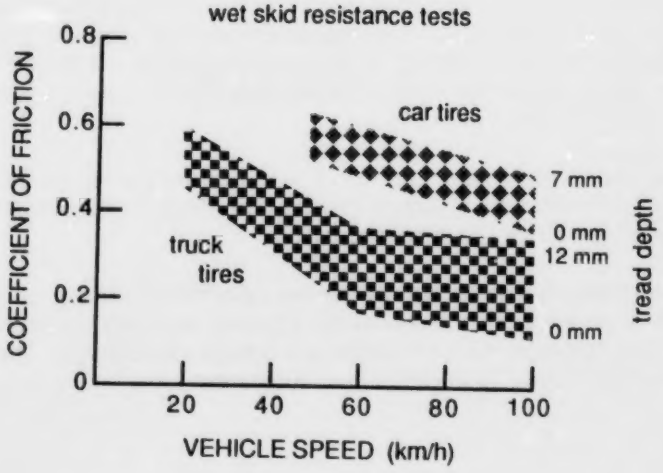


Figure 3. Tire-Pavement Friction Coefficients for Car and Truck Tires

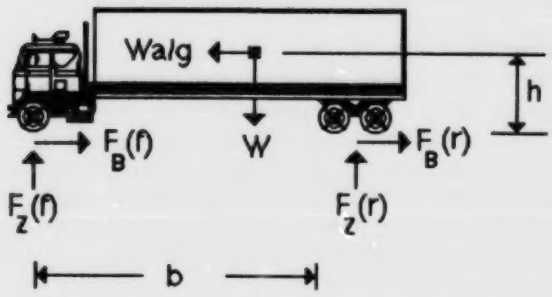


Figure 4. Forces Acting on 3 - Axle Truck During Braking

Load is transferred from the rear to front axles during braking and the maximum magnitude of this load transfer depends on the height of the centre of mass of the vehicle, the length of the wheelbase and the magnitude of the tire-pavement friction. The normal forces on the front and rear axles at maximum braking may be derived from Figure 4 and these are :

[2] $$F_Z(f) = W(f) + Wf\,\frac{h}{b}$$

[3] $$F_Z(r) = W(r) - Wf\,\frac{h}{b}$$

where $F_Z(f)$, $F_Z(r)$ = the normal forces acting through the front and rear axles, respectively ; W = the weight of the vehicle ; W (f), W (r) = the static normal forces acting through the front and rear axles, respectively ; h = the height of the centre of mass above the pavement ; b = the wheelbase of the vehicle ; f = the tire-pavement coefficient of friction.

Eqns [2] and [3] may be divided by the total vehicle weight W to give the ideal proportions of the brake forces on the front and rear axles and these are :

[4] $$P(f) = \frac{W(f)}{W} + \frac{f\,h}{b}$$

[5] $$P(r) = \frac{W(r)}{W} - \frac{f\,h}{b}$$

The proportions of front and rear braking calculated from eqns [4] and [5] are ideal in the sense that they have the same magnitudes as the proportions of the total load transmitted through the two axle groups at maximum braking.

Variations in Ideal Braking Proportions

Figure 5 shows the variation in the proportion of braking on the front axle for ideal braking for the loaded and unloaded conditions and for a variety of tire-pavement friction coefficients. For example, at a tire-pavement coefficient of friction of 0.2, ideal braking would require 35 percent of the braking on the front axle for the loaded condition and 44 percent for the unloaded condition. The diagram also shows that the proportion of front axle braking for ideal braking increases from 35 percent at a coefficient of friction of 0.2 to about 57 percent for a coefficient of friction of 0.8 for the loaded truck. These changing ideal brake proportions reflect the changing proportions of vehicle mass (tare + load) transmitted respectively through the front and rear axles. The front brake proportion increases with increasing magnitude of the coefficient of friction as this reflects the greater load shift to the front axle under maximum braking. With a fixed brake system and widely varying load and road conditions, braking system performance may often be less than ideal.

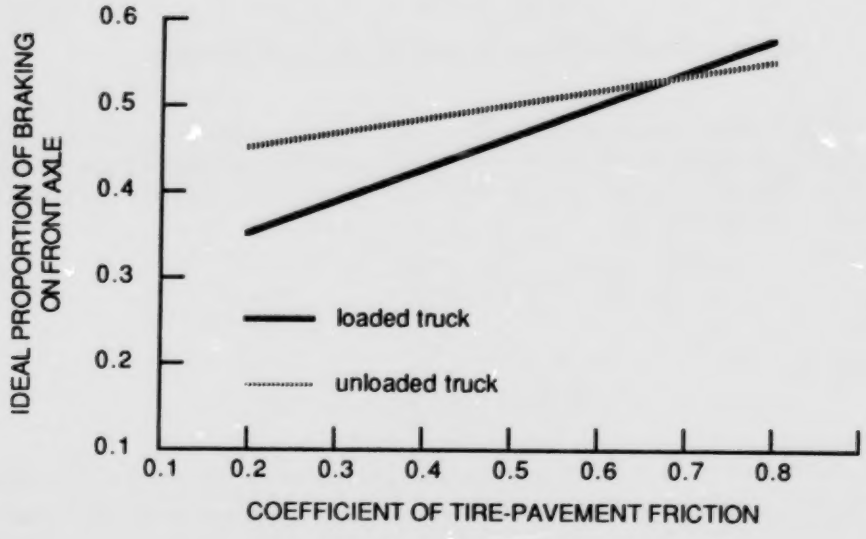


Figure 5. Variation in Front Axle Braking Proportion Required to Achieve Ideal Braking

Maximum Decelerations

The maximum deceleration of a vehicle is obtained when the braking force developed at the tire-pavement interface at each wheel is just equal to the product of the normal force at each wheel and the tire-pavement coefficient of friction. If the braking force developed at one or more wheels exceeds the friction force at these wheels, then wheel lock-up will occur at these wheels. If controlled braking is to be achieved then the maximum deceleration of a vehicle is governed by the braking force that is being developed at the wheel which first locks up.

It has been pointed out earlier that a second case may exist and this occurs when a brake system cannot develop a brake torque at each tire-pavement interface that is equal to the maximum frictional force that could be developed. This means that the maximum possible deceleration could not be achieved. Limited brake torque may occur on under-braked trucks or on trucks with poor friction characteristics at the brake lining-brake drum interface (eg. wet brakes or overheated brakes) or with improperly adjusted brakes.

Braking efficiency may be defined as the ratio of the maximum deceleration that may be achieved by a truck divided by the coefficient of tire-pavement friction :

[6] $$n = \frac{a}{f}$$

where n = the braking efficiency; a = the deceleration achieved by a truck with a given axle load distribution, brake forces and tire-pavement friction in units of g; f = the tire-pavement coefficient of friction.

1.3 Clearance Times

Figure 6 shows a hypothetical signal timing sequence for a two-phase signalized intersection. The signal aspect for each phase changes from green through amber to red and the signal timing includes an all-red period between phases. The amber plus all-red time for each phase is the clearance time between the green times of the two phases.

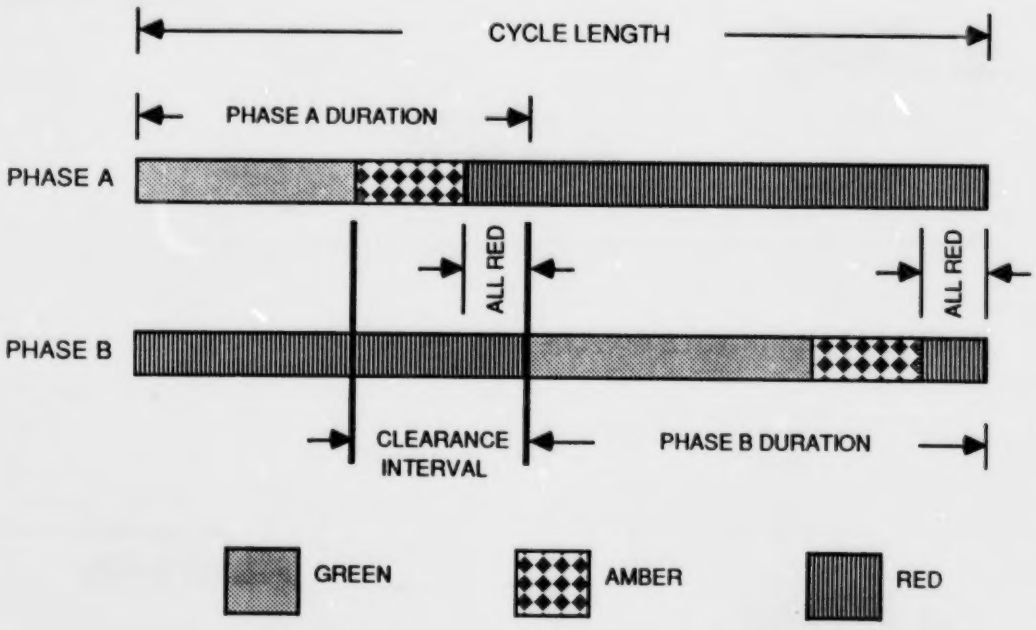


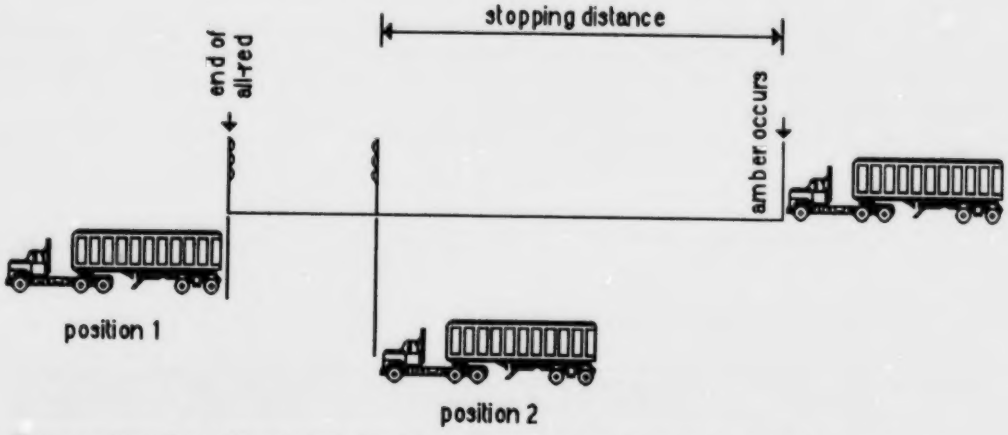
Figure 6. Signal Timing Sequence for Two Phase Signalized Intersection

The clearance time must be sufficiently long to allow a driver who is close to the intersection to react to an amber signal and brake safely to a stop before reaching the signal stop bar. The components of this clearance time are illustrated in Figure 7 and these consist of (i) the time taken by a driver to react to an amber signal (usually set at 1 s) ; (ii) the time required to travel the stopping distance at the operating speed ; (iii) the time required for the front of a vehicle to travel across the width of an intersection; and, (iv) the time required for the length of a vehicle to pass a point at the operating speed. The Institute of Transportation Engineers (4) standards assume that a vehicle deceleration of 0.31 g (10 ft/s^2) may be achieved during braking. This means that a clearance time for a standard tractor semi-trailer operating at 80 km/h would be :

perception / reaction time	1.00 s	
time to travel stopping distance	3.84 s	
time across intersection	0.68 s	
time for length of truck	0.84 s	total = 6.2 s

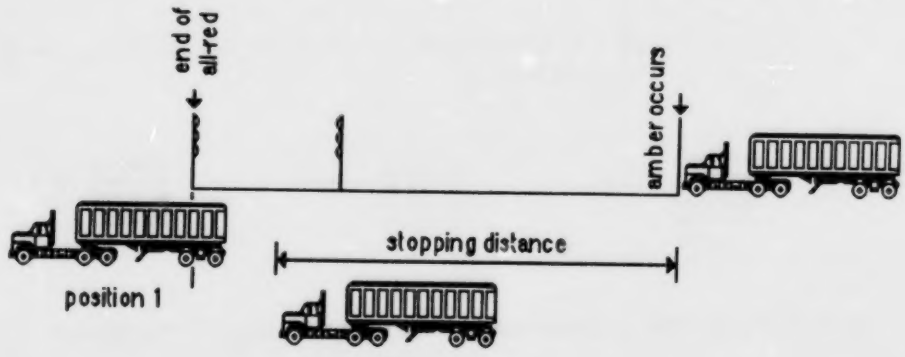
CLEARANCE TIME WITHOUT A DILEMMA ZONE

stopping distance = brake reaction distance + braking distance



clearance time allows driver to just clear intersection (position 1) or to brake to a stop (position 2)

CLEARANCE TIME WITH A DILEMMA ZONE



clearance time is insufficient to allow driver to clear intersection (position 1) or to brake before entering intersection (position 2)

Figure 7. Concept of Desirable Signal Clearance Time

1.4 Parametric Emphasis of the Study

The approach taken to realize the objectives of this study has been to establish simplified braking models for each truck type and to calculate the braking distances, braking efficiencies and clearance times for a range of speeds, truck loading conditions and magnitudes of tire-pavement friction. The parameters required by these models have been obtained from a variety of sources and these sources are carefully documented throughout the report.

The parametric emphasis of the study has been pursued because there are few sources of field data which provide braking distances and times, mass and dimension characteristics, braking system properties and tire-pavement friction magnitudes for a range of vehicle types. The parametric nature of the study should be remembered when the results presented in the subsequent chapters are being reviewed. The results contained in this study should provide a basis for designing appropriate field tests of truck braking capabilities if field tests are deemed to be necessary to validate the theoretical results.

1.5 Structure of the Report

Chapter 2 provides a detailed description of the simplified braking models that have been developed for a range of truck types and implemented as spreadsheets on Lotus 123. Chapter 2 is supported by a separate technical volume which describes the structure of each of the spreadsheets in detail.

Chapters 3 through 7 summarize the braking distance, braking efficiency and clearance time results calculated for each of the truck types for a range of speeds, tire-pavement frictions and loading conditions.

Chapters 8, 9 and 10 provide respectively, a comparison of the braking distances, braking efficiencies and clearance times across each of the truck types. Available empirical evidence on truck braking characteristics is also summarized in these chapters and related to the simulated behaviour of the different truck types.

Chapter 11 describes the analysis of the MTC truck accident records for 1983 and attempts to relate some of the findings of this analysis to the braking properties estimated by the simplified models.

Finally, Chapter 12 provides a comprehensive summary of the technical findings of this study along with the important assumptions that were necessary in a study of this type.

CHAPTER 2

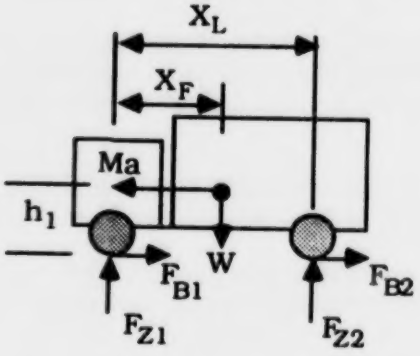
SIMPLIFIED BRAKING MODELS

2.1 The Nature of the Models

This chapter describes the simplified models used to estimate the braking characteristics of trucks and these models are based on those developed by the University of Michigan Transportation Research Institute (UMTRI) and reported by Ervin and Guy (1) and Mathew (5). The equations used to estimate the behaviour of each of the vehicle components in single and multiple unit vehicles are described in the following sections of this chapter. The spreadsheets written to solve the equations for particular truck configurations are described in a separate technical report. The subsequent chapters of this report describe the applications of these braking models.

2.2 Straight Trucks

Figure 8 illustrates the free body diagram for a 2-axle truck along with the forces acting on the truck during braking and the critical dimensions of the truck. The braking forces developed at the tire-pavement interface, F_{B1} and F_{B2}, provide the retarding force (rolling resistance and drag are neglected).



[7] $$a = \frac{(F_{B1} + F_{B2})}{M}$$

[8] $$F_{Z2} = \frac{(W X_F - M a h_1)}{X_L}$$

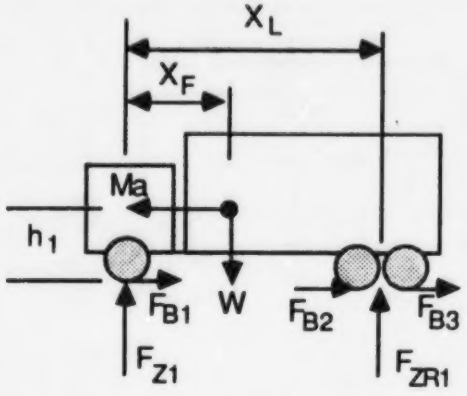
[9] $$F_{Z1} = W - F_{Z2}$$

[10] $$M = \frac{W}{g}$$

Figure 8. Equations of Dynamic Equilibrium for a Two-Axle Truck

The deceleration of the vehicle is obtained by dividing the retarding force by the mass of the vehicle as shown by eqn [7] in Figure 8. The rear axle load, F_{Z2}, is calculated by eqn [8] by taking the moments about the front tire-pavement contact. The front axle load, F_{Z1}, is calculated by eqn [9] from the summation of the forces acting in the vertical direction.

Figure 9 illustrates the free body diagram for a 3-axle truck along with the forces acting on the truck. The only difference from Figure 8 is the braking force developed at the second axle of the tandem. It is assumed that there is no dynamic load transfer between axles in an axle group. The tandem apparatus is assumed to divide the reaction equally between the two axles at all times. It has been established that some suspension types will exhibit a small load shift to either the rear or forward axle during braking. For example, a 4-spring type suspension will exhibit a shift to the rearward axle. This would have some influence on the level of deceleration at which the tandem would become laterally unstable, but a sensitivity analysis showed the effect to be negligible. In these analyses, the effect of any intra-tandem load shift has been neglected and the reaction on each axle in a tandem is half of the reaction calculated for the tandem group.



[11] $$a = \frac{(F_{B1} + F_{B2} + F_{B3})}{M}$$

[12] $$F_{ZR1} = \frac{(WX_F - Mah_1)}{X_L}$$

[13] $$F_{Z1} = W - F_{ZR1}$$

Figure 9. Equations of Dynamic Equilibrium for a Three-Axle Truck

Inspection of eqn [8] for the 2-axle truck and eqn [12] for the 3-axle truck shows that the vertical load on the rear axle during braking (and therefore, the front axle as well) is influenced by the locaton of the centre of mass, the wheelbase and the deceleration magnitude. The location of the centre of mass will change as trucks are loaded with payloads of different densities and this shift has a significant influence on the braking efficiencies of trucks.

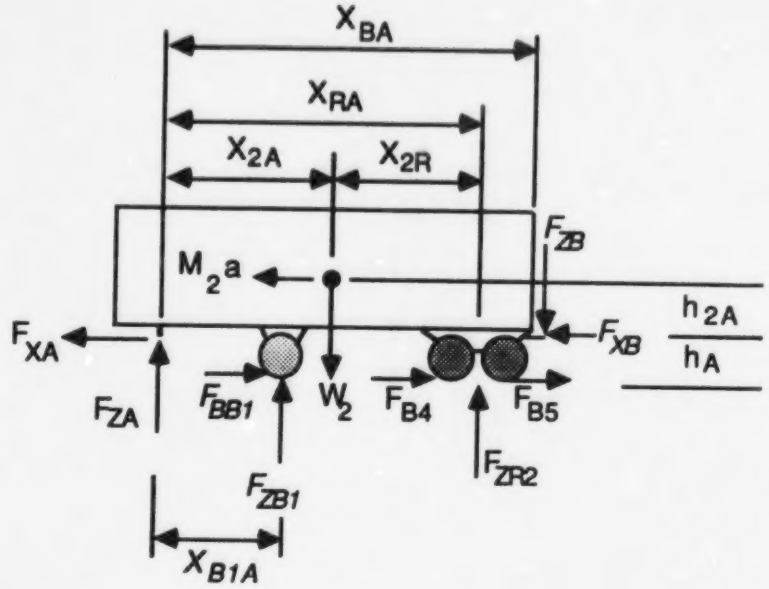
2.3 Semi-Trailers

Figure 10 illustrates the free body diagram for a semi-trailer which includes the option for a belly axle as well as for the transfer of forces from the rear units in double trailer combinations. These optional forces

and dimensions are shown in italics in the equations.

The forces acting on the fifth wheel of the semi-trailer should be noted and these include the horizontal force, F_{XA}, and the normal force, F_{ZA}, transmitted to the tractor.

Equation [14] captures the equilibrium of the horizontal forces and allows the force transmitted to the tractor through the point of articulation to be calculated. The magnitude of the vertical load transmitted through the rear axle group to the pavement, F_{ZR2}, is calculated by eqn [15] in which moments are taken about the point of articulation. The vertical load transmitted through the articulation point, F_{ZA}, is calculated by eqn [16] by summing the vertical forces.



[14] $$F_{XA} = F_{B4} + F_{B5} + F_{BB1} - M_2 a + F_{XB}$$

[15] $$F_{ZR2} = \frac{[M_2 a h_{2A} + (F_{B4} + F_{B5} + F_{BB1}) h_A + F_{ZB1} X_{B1A} - X_{2A} W_2 - F_{ZB} X_{BA}]}{-X_{RA}}$$

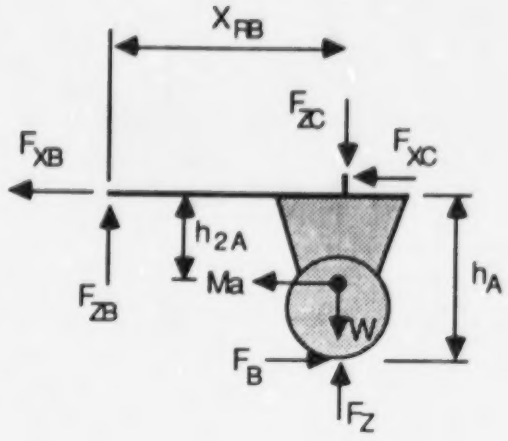
[16] $$F_{ZA} = W_2 + F_{ZB} - F_{ZR2} - F_{ZB1}$$

Figure 10. Equations of Dynamic Equilibrium for Semi-trailer

2.4 Converter Dollys

Converter dollys are used to connect the trailers in multiple trailer configurations and Figure 11 illustrates the free body diagram for a converter dolly. Horizontal and vertical loads are transferred to it from the semi-trailer it supports and it transfers in turn forces to the trailer which tows it. The equations for the converter dolly are the same as those for a semi-trailer with one axle and a centre of mass located below the point of articulation. Equation [17] solves for the horizontal force transmitted to the lead trailer while eqn [18] solves for the vertical load transmitted through the axle of the converter dolly to the pavement by taking

moments about the point of articulation. Equation [19] solves for the vertical load transmitted through the point of articulation.



[17] $$F_{XB} = F_{XC} + F_B - Ma$$

[18] $$F_Z = \frac{(F_{ZC} X_{RB} + W X_{RB} + Ma h_{2A} - F_B h_A)}{X_{RB}}$$

[19] $$F_{ZB} = W + F_{ZC} - F_Z$$

Figure 11. Equations of Dynamic Equilibrium for Converter Dolly

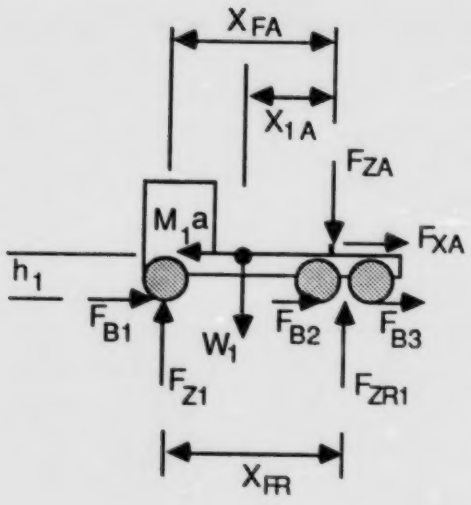
2.5 Tractors

Figure 12 illustrates the free body diagram for a tractor. The forces acting on the tractor include those acting on straight trucks as well as the horizontal and vertical forces transmitted to the tractor from a semi-trailer through the fifth wheel.

Equation [20] solves for the vertical load transferred through the tractor rear axle group by taking moments about the point of contact between the pavement and the front tires. The vertical load transferred through the steering axle is calculated by eqn [21] which sums the vertical forces acting on the tractor.

2.6 Solving the Equations

The braking characteristics of each of the vehicles evaluated in this study were analyzed by combining equations for the appropriate truck elements into a system of equations for a particular truck design. The equations were used to estimate the level of braking at which wheel lock-up first occurred by solving the system of equations for each of several levels of braking. This step-wise approach [same as used by UMTRI (1)] is required since the vertical loads transmitted through each axle to the pavement vary with the deceleration magnitude.



[20] $$F_{ZR1} = \frac{(M_1 a h_1 - F_{ZA} X_{FA} - F_{XA} h_A - W_1 X_{1F})}{-X_{FR}}$$

[21] $$F_{Z1} = W_1 + F_{ZA} - F_{ZR1}$$

Figure 12. Equations of Dynamic Equilibrium for a Tractor

There are many factors which the simplified models do not take into account including different coefficients of tire-pavement friction at each axle, differential loading between wheels at an axle, and the fact that drivers cannot be expected to select immediately and maintain the maximum level of braking at which vehicle control still exists. These models, as is later demonstrated in a limited validation, do provide a reasonable estimate of the stopping distances and provide a good indication of the relative performance of various vehicles at different loadings, speeds and coefficients of friction relative to existing design standards. Caution should be exercised in interpreting individual results in any absolute way. Insufficient empirical evidence exists to evaluate the models over a range of conditions.

The UMTRI model has been implemented in the form of a Lotus 123 spreadsheet for each vehicle for ease of use in testing a variety of conditions. The model was extended at the input and output stages and calculates automatically the location of the centre of mass for a vehicle under a variable load, with a loading area divided longitudinally into ten sections, each of which may be loaded to a user-defined height with a material of user-defined density. This was necessary to provide the required degree of flexibility to test the implications of a variety of vertical load distributions on braking performance. In addition to calculating the vertical axle loads at each level of braking, the spreadsheet uses the coefficient of tire-pavement friction to interpolate the maximum deceleration achievable under control. This allows the measures of effectiveness to be calculated where these are the braking distance, the braking efficiency (deceleration in g's divided by the coefficient of friction) and the clearance time required to prevent the existence of a dilemma zone.

Eleven spreadsheets were developed for this study and these are listed below along with the truck types analyzed by each spreadsheet :

1. BR2.WK1: 2-axle straight truck,
2. BR3.WK1: 3-axle straight truck, bobtail tractor,

3. BR3S2.WK1: 3-axle tractor with a tandem axled semi-trailer, similar vehicles but with raised belly axles,
4. BR3S3B1.WK1: 3-axle tractor with a tandem axled semi-trailer and one lowered belly axle,
5. BR3S4B2.WK1: 3-axle tractor with a tandem axled semi-trailer and two lowered belly axles,
6. BR3S3.WK1: 3-axle tractor with a tridem axled semi-trailer and one or two raised belly axles,
7. BR3S4B1.WK1: 3-axle tractor with a tridem axled semi-trailer and one lowered belly axle,
8. BR3S5B2.WK1: 3-axle tractor with a tridem axled semi-trailer and two lowered belly axles,
9. BR3S12.WK1: 3-axle tractor with a single axled semi-trailer and a second 2-axle trailer,
10. BR3S2S2.WK1: 3-axle tractor with a tandem axled semi-trailer and a second tandem axled semi-trailer,
11. BR3S3S2.WK1: 3-axle tractor with a tridem axled semi-trailer and a second tandem axled semi-trailer.

CHAPTER 3

BRAKING CAPABILITIES OF STRAIGHT TRUCKS

3.1 Introduction

The simplified braking model described in Chapter 2 calculated the braking forces that could be developed at each wheel from the product of the normal forces on a wheel at various levels of brake application and the coefficient of tire-pavement friction. The normal force at each wheel reflects both the static load and the load shift between axles which occurs during braking. It should be recalled that the maximum braking force that can be developed is governed by the wheel that first locks up.

3.2 Properties of the Two-Axle Straight Truck

Figure 13 illustrates the dimensions of the 2-axle straight truck that was analyzed and Table 2 summarizes its mass and dimension characteristics. The mass and dimension characteristics were obtained from FHWA braking test vehicles reported by Radlinski and Williams (7).

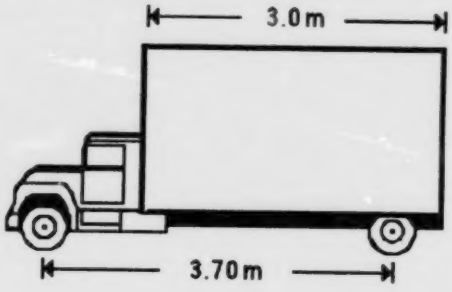


Figure 13. Dimensions of Two-Axle Straight Truck

Table 2. Mass and Dimension Properties of Two-Axle Truck

mass (kg)	4 364
centre of mass height (m)	0.75
front axle to box front (m)	1.00
box front to c of m (m)	0.85
box length (m)	3.00
box width (m)	2.50
front axle to rear axle (m)	3.70
height of loading bed (m)	1.07

The vehicles have been equipped with brakes having the brake torque versus brake line pressure response reported by Radlinski and Williams (7). The brake forces developed at each axle from four increments of brake line pressure are summarized in Table 3 for the 2-axle truck for a speed of 60 km/h. Post et al (6) have shown that the brake forces that can be developed vary with speed. In these analyses the following multipliers have been used to estimate the brake forces that may be developed at different speeds:

initial speed (km/h)	40	60	80	100
brake force multiplier	1.1	1.0	0.9	0.8

Table 3. Brake Characteristics of Two-Axle Truck

60 km/h brake forces table

Pressure (psi)	0	20	40	60	80
Axle 1 (N)	0	8 010	13 796	24 030	25 810
Axle 2 (N)	0	8 900	26 700	33 376	41 386

The 2-axle truck has been loaded with a typical light cargo (1 000 N/m^3) of the type transported by vehicles which "cube-out". Three load conditions were tested and these are:

1. fully loaded and this means a GVM of 6 420 kg for the 2-axle truck given the assumed cargo density,
2. half unloaded from the rear and top, respectively, and this means a GVM of 5 392 kg,
3. unloaded.

3.3 Properties of the Three-Axle Straight Truck

Figure 14 shows the dimensions of the 3-axle truck analyzed in this study while Table 4 lists in detail its mass and dimension characteristics and Table 5 its brake properties. Both sets of characteristics were taken from Radlinski and Williams (7).

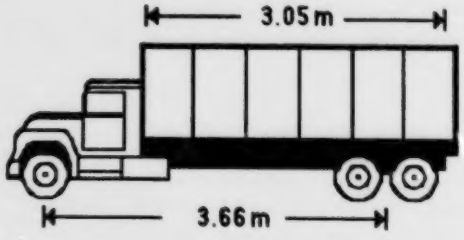


Figure 14. Dimensions of Three-Axle Straight Truck

Table 4. Mass and Dimension Properties of the Three-Axle Truck

mass (kg)	8 619
centre of mass height (m)	0.75
front axle to box front (m)	1.50
box front to c of m (m)	0.80
box length (m)	3.05
box width (m)	2.29
front axle to rear axle (m)	3.05
height of loading bed (m)	1.07

Table 5. Brake Characteristics of Three-Axle Truck

60 km/h brake forces table

Pressure (psi)	0	20	40	60	80
Axle 1 (N)	0	7 566	16 910	24 030	32 486
Axle 2 (N)	0	13 796	40 050	49 840	58 740
Axle 3 (N)	0	13 796	40 050	49 840	58 740

The loading used for the 3-axle truck has a density of 17 000 N/m^3 to reflect a typical gravel cargo and this resulted in fully loaded mass of 24 809 kg for the 3-axle truck and 16 714 kg for the half-loaded truck.

3.4 Braking Conditions Analysed

The braking capabilities of the straight trucks and all of the other vehicle configurations to be discussed in later chapters have been analysed for :

1. the appropriate load conditions for the vehicle configuration,
2. operating speeds from 40 to 100 km/h, and
3. pavement conditions ranging from a coefficient of friction of 0.2 (ice) to 0.8 (dry pavement with good surface texture and unworn tires).

3.5 Braking Distances

The braking distances estimated for each set of test conditions are calculated from the deceleration which is achieved just as the first axle locks up. It is assumed for the purpose of the simplified braking model that the driver is capable of instantly achieving and maintaining this maximum deceleration and of maintaining vehicle control so that the vehicle does not deviate from its traffic lane during braking.

Two-Axle Truck

Figure 15 illustrates the braking distances required to stop the 2-axle truck from 80 km/h for four coefficients of friction under the three loading conditions. It should be recalled that a coefficient of friction of 0.2 is typical of icy pavements while one of 0.8 is typical of new tires operating on dry pavements with excellent surface conditions.The current braking distance standard of 81 m for an 80 km/h design speed is also indicated on both diagrams and it should be recognized that this standard is based on an assumed coefficient of tire-pavement friction of 0.31 (8).

Figure 15 illustrates that the 2-axle truck can achieve the RTAC braking distance standard at 80 km/h for coefficients of friction greater than 0.4. Variations in the truck loading conditions have little influence on the braking distances except at the lowest coefficient of friction of 0.2. For icy conditions the half-loaded and unloaded trucks experience increases in braking distances of about 20 m and 10 m, respectively. This is a result of underloading at the rear axle under conditions other than a full load. At coefficients of friction about equal to those assumed in the geometric design standards, the straight trucks require braking distances about 1.4 times as long as those specified in the standards.

Three-Axle Truck

Figure 16 shows the braking distances calculated for the 3-axle truck for the various combinations of friction and speed. The 3-axle truck requires similar braking distances to the 2-axle truck, except at the lowest coefficient of friction where the braking distances are about 15 percent higher.

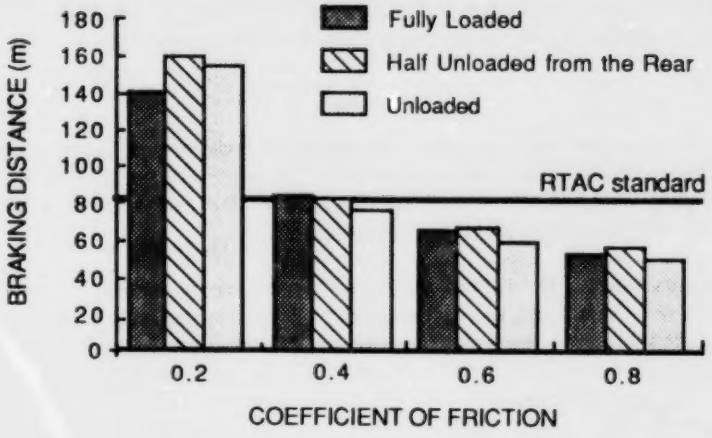


Figure 15. Braking Distances for Two-axle Truck from 80 km/h for Various Coefficients of Friction

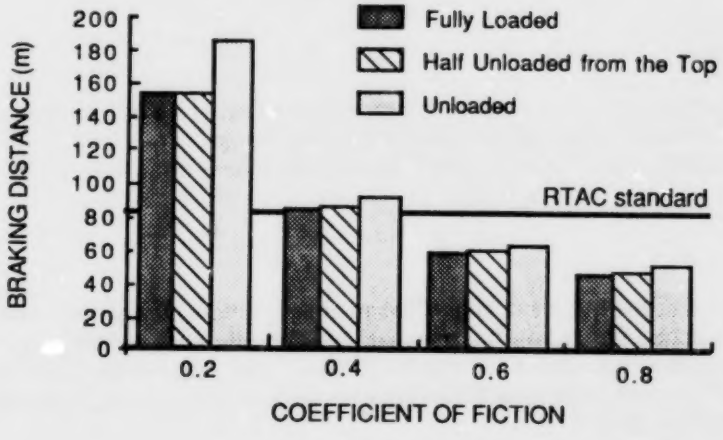


Figure 16. Braking Distances for Three-axle Truck from 80 km/h for Various Coefficients of Friction

For all of the loading, friction and speed conditions tested, the braking performance of the straight trucks were limited by the premature lockup of the rear axle. This indicates that the distributions of the vertical loads during braking were not proportional to the braking power distribution, with the rear axle or tandem being underloaded. When the underloading is more severe, as when the vehicle is partially or completely unloaded, the premature lockup occurs at a lower level of braking.

Effects of Speed

Figure 17 illustrates the influence of speed on the braking distances required by the half-unloaded 2-axle truck over the range of coefficients of friction tested while Figure 18 shows these relationships for the unloaded 3-axle truck. These load conditions are examined because they result in the worst performance for each vehicle as shown previously in Figures 15 and 16, respectively.

The hatched areas show the braking distances which are in excess of those specified in the geometric design standards. It should be recognized that the coeffcients of friction assumed in the geometric design standards increase marginally with speed. The diagrams illustrate that the straight trucks can only achieve these standards for coefficients of friction greater than about 0.5.

Load Shifts on Tandem Axles

It must be noted that with some tandem axle suspension systems there is a dynamic load shift between the two axles during braking in addition to any shift of load to the forward axles. This has not been included in the model. For example, it has been reported by UMTRI (2,3) that a 4-spring type suspension tends to produce a slight load shift to the trailing axle during the braking maneuver. Where a tandem is experiencing the premature lockup which is limiting braking performance, it is assumed that both axles in the tandem must be locked before the tandem as a unit will experience lateral instability. Since the intra-tandem load shift serves to increase the loading of one of the axles it allows the vehicle to achieve a slightly higher level of deceleration before the braking must be limited to avoid wheel lock-up. In this respect, these results tend to understate the braking capability of the vehicles, but a sensitivity analysis has shown that the effect is negligible.

3.6 Braking Efficiencies

Braking efficiency has been defined in Chapter 1 as the ratio of the deceleration achieved by a truck in units of g (acceleration due to gravity) to the coefficient of tire-pavement friction. The RTAC draft standards (10) suggest that a braking efficiency of at least 70 percent should be achievable by trucks under any combination of loading and pavement condition.

Two-Axle Truck

Figure 19 illustrates the maximum and minimum braking efficiencies of the 2-axle truck for the three load conditions. The hatched bar shows the minimum braking efficiency for the range of coefficients of friction tested, while the open bar shows the maximum value. The diagram illustrates that the 70 percent braking efficiency standard is not met by the 2-axle truck for some of the test conditions with minimum values being just greater than 50 percent.

Three-Axle Truck

Figure 20 illustrates the range of braking efficiencies achieved by the 3-axle truck. The minimum braking efficiencies are higher than for the 2-axle truck although the maximum braking efficiency achieved by the unloaded 3-axle truck does achieve the 70 percent braking efficiency standard.

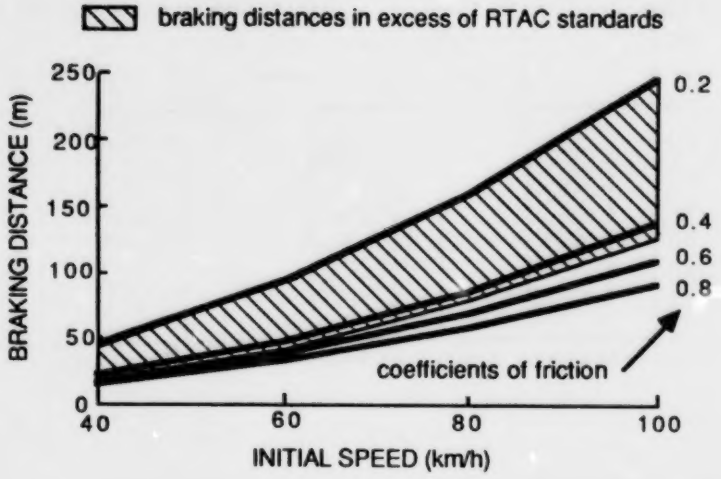


Figure 17. Braking Distances for Two-Axle Truck Half Unloaded From the Rear from Various Speeds

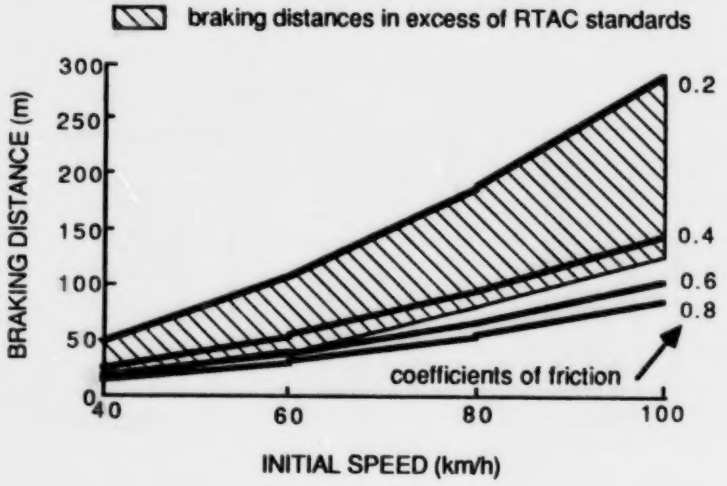


Figure 18. Braking Distances for an Unloaded Three-Axle Truck from Various Speeds

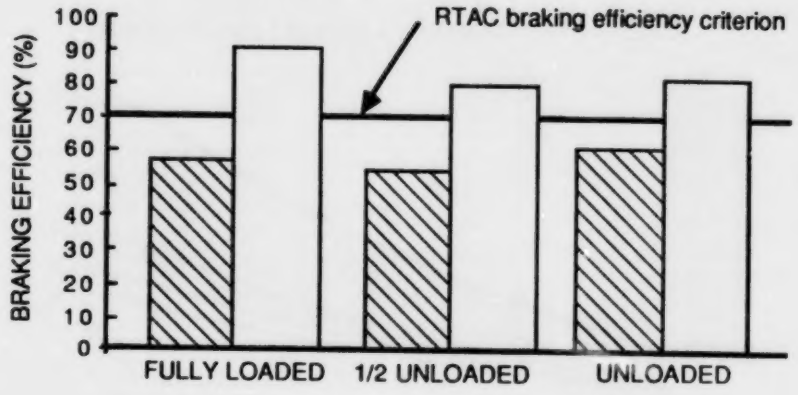


Figure 19. Minimum and Maximum Braking Efficiencies for Two-Axle Truck

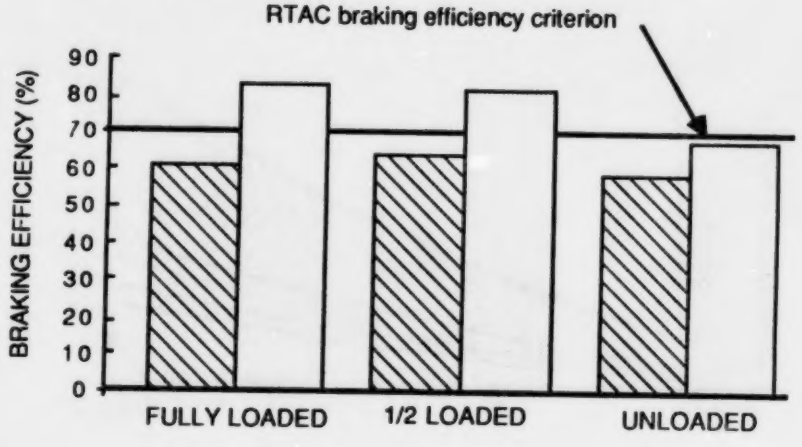


Figure 20. Minimum and Maximum Braking Efficiencies for Three-Axle Truck

3.7 Clearance Times

It has been pointed out in Chapter 1 that an important component of the inter-phase clearance time required at signalized intersections is the braking time required by trucks. The clearance time consists of four components and these are an initial perception/reaction time, the time required to travel the braking distance, the time for the front of a truck to cross an intersection and the time for a truck of a given length to pass a point in an intersection.

Two-Axle Truck

Figure 21 illustrates the signal clearance times required for the 2-axle truck half unloaded from the rear as a function of both its initial speed and the tire-pavement coefficient of friction. The diagrams highlight the combinations of speed and coefficient of friction for which the clearance times calculated using the ITE standard (4) cannot be achieved. It should be recalled that this standard assumes that vehicles are capable of achieving a deceleration rate of 0.31 g. Figure 21 illustrates that the 2-axle truck is capable of achieving this standard providing the coefficient of tire-pavement friction is greater than about 0.5.

Three-Axle Truck

Figure 22 presents these results for the unloaded 3-axle truck and this diagram illustrates similar behaviour for the 3-axle truck. The limiting coefficient of tire-pavement friction is marginally higher for the worst case for the 3-axle truck and this reflects the lower braking efficiency illustrated in Figure 20 for the unloaded truck.

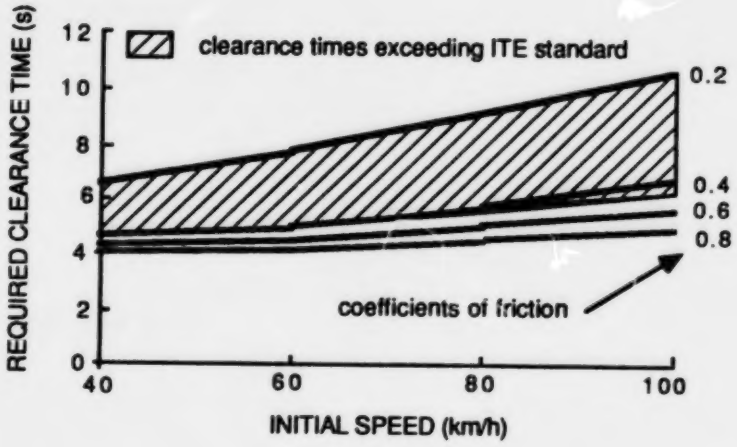


Figure 21. Clearance Times Required by Two-Axle Truck Half Unloaded from the Rear from Various Speeds

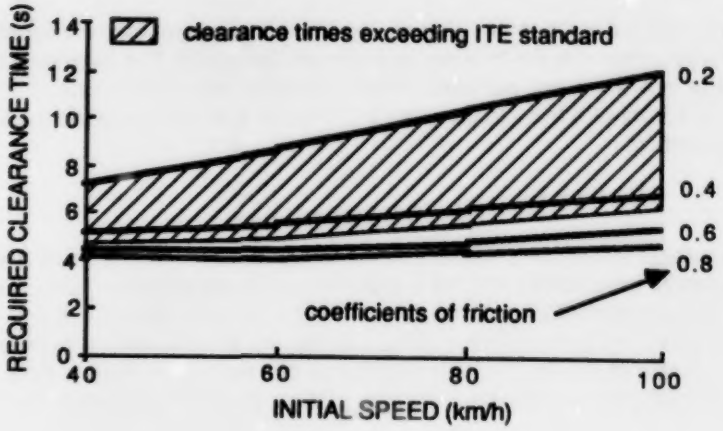


Figure 22. Clearance Times Required by Unloaded Three-Axle Truck from Various Speeds

CHAPTER 4

BRAKING CAPABILITIES OF TRACTOR SEMI-TRAILERS

4.1 Introduction

The braking model for the tractor semi-trailer differs from that developed for the straight truck in that vertical and horizontal forces are transmitted from the semi-trailer to the tractor through the fifth wheel. The forces transmitted through the fifth wheel during braking are a function of the initial speed, load condition, and the tire-pavement friction.

4.2 Properties of the 3-S2

Figure 23 illustrates the dimensions of the 3-S2 tractor semi-trailer analysed in these braking studies while Table 6 summarizes its detailed mass and dimension characteristics. The properties were assembled from a Canroad test vehicle (1) and supplemented by data obtained from the Freuhauf Trailer Company of Canada and the University of Calgary.

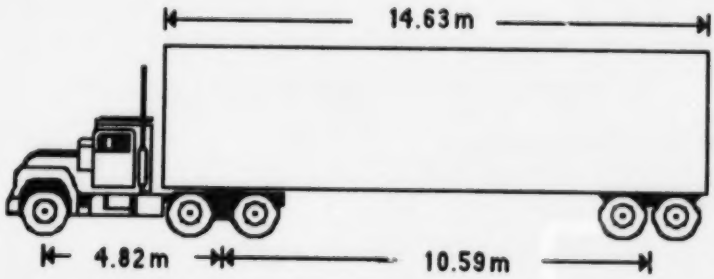


Figure 23. Dimensions of 3-S2 Tractor Semi-Trailer

The vehicle has been equipped with brakes having the brake torque versus brake line pressure response reported by Radlinski and Williams (7). The brake forces developed at each axle from four increments of brake line pressure are summarized in Table 7. The table shows that the brake forces developed at the front axle are about one-half of those developed at the tractor and semi-trailer tandems for the higher brake line pressures.

The 3-S2 has been loaded with a typical light cargo (1000 N/m^3) of the type transported by vehicles which "cube-out". Four load conditions were tested and these are:

1. fully loaded and this results in a GVM of 24 537 kg,
2. half unloaded from the rear of the semi-trailer and this results in a GVM of 19 518 kg,
3. unloaded, and
4. the tractor alone (bobtail).

Table 6. Mass and Dimension Properties of 3-S2

Tractor - 3 axles	
mass (kg)	8 200
centre of mass height (m)	0.88
fifth wheel height (m)	1.22
front axle to c of m (m)	2.41
c of m to rear axle (m)	1.65
c of m to last axle (m)	3.18
c of m to fifth wheel (m)	2.03
Unloaded semi-trailer - 2 axles	
mass (kg)	6 300
length (m)	14.63
width (m)	2.50
king pin set-back (m)	0.91
leading edge to rear axle (m)	12.65
leading edge to last axle (m)	13.87
leading edge to c of m (m)	7.82
c of m height (m)	1.27
height of loading bed (m)	1.37

Table 7. Brake Characteristics of 3-S2

60 km/h brake forces table

Pressure (psi):	0	20	60	80	100
Axle 1 (N):	0	0	16 910	20 026	23 142
Axle 2 (N):	0	8 900	36 046	44 056	52 066
Axle 3 (N):	0	8 900	36 046	44 056	52 066
Axle 4 (N):	0	9 346	30 706	42 276	52 586
Axle 5 (N):	0	9 346	30 706	42 276	52 586

4.3 Braking Distances

Figure 24 illustrates the braking distances required to stop from 80 km/h for four coefficients of friction under the four load conditions. The current braking distance standard for an 80 km/h design speed of 81 m is also indicated on the diagram. This standard is based on an assumed coefficient of tire-pavement friction of 0.31. The diagram illustrates that fully loaded vehicles can only achieve this braking distance standard when the available coefficient of friction exceeds about 0.4 and that partially-loaded and unloaded vehicles as well as bobtail tractors require coefficients of friction close to 0.8. For all of the loading, friction, and speed conditions tested the braking performance of the 3-S2 was limited by the premature lockup of the rear tandem. This indicates that the distribution of the vertical loads during braking were not proportional to the braking power distribution, with the rear tandem being underloaded (alternatively, overbraked). When the underloading is more severe such as when the vehicle is unloaded, the premature lockup occurs at a lower level of braking.

An important feature illustrated by Figure 24 is the poor braking distance behaviour of the partially

loaded and unloaded vehicles as well as the bobtail tractor at the low coefficients of friction. Even at coefficients of friction marginally higher than those assumed in the geometric design standards, the less than fully loaded 3-S2 requires braking distances about twice as long as those specified in the standards.

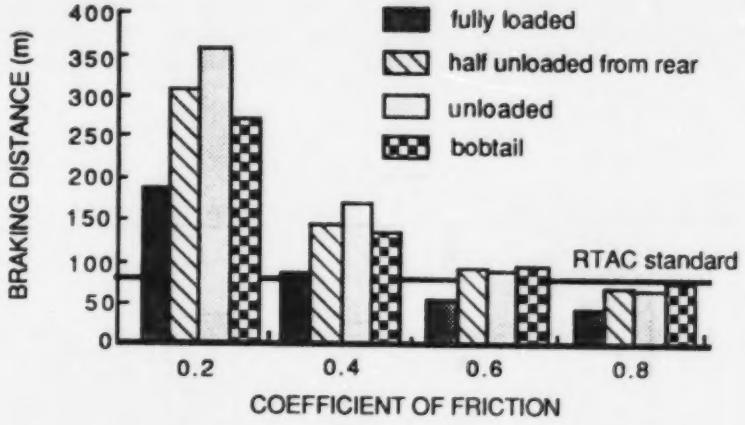


Figure 24. Braking Distances for 3-S2 from 80 km/h for Various Coefficients of Friction

Figure 25 illustrates the influence of speed on the braking distances required by an unloaded 3-S2 over the range of coefficients of friction tested. This variation is examined for the unloaded condition because this represents the worst performance for the vehicle as illustrated in Figure 24. The hatched area shows the braking distances which are in excess of those specified in the geometric design standards. The unloaded 3-S2 can only achieve these standards for coefficients of friction greater than about 0.7. It should be recalled that this critical coefficient of friction was only about 0.5 for the straight trucks which emphasizes the inferior braking characteristics of this lightly loaded 3-S2.

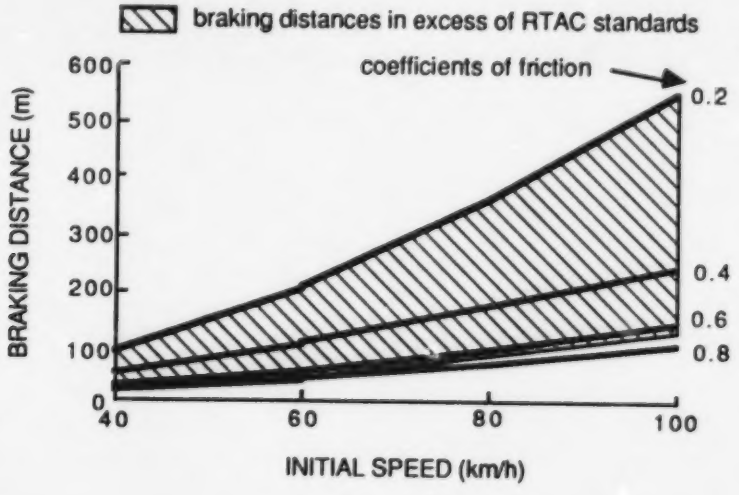


Figure 25. Braking Distances for Unloaded 3-S2 from Various Speeds

4.4 Braking Efficiencies

Figure 26 illustrates the maximum and minimum braking efficiencies for the four load conditions. The range of braking efficiencies results from the variation in the coefficients of friction and speeds. The diagram also shows the proposed RTAC braking efficiency criterion of 70 percent and illustrates that only the fully-loaded vehicle is capable of achieving this criterion. This is reasonable since the brake characteristics specified in Table 7 are proportioned for the loaded condition. The braking efficiencies for the straight trucks illustrated in Figures 19 and 20 are systematically higher than those illustrated in Figure 26 for the 3-S2.

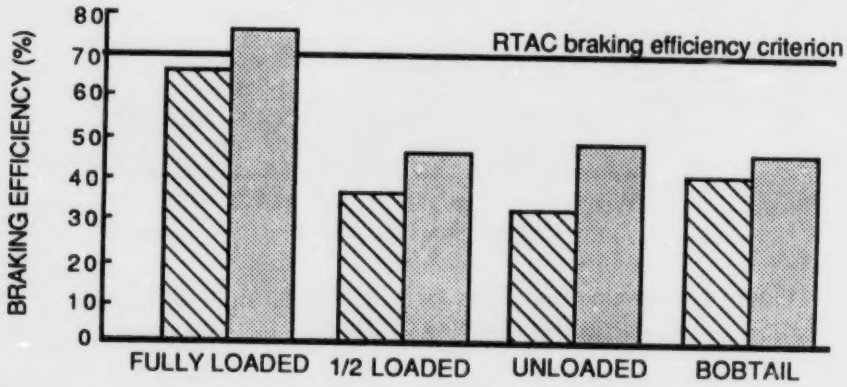


Figure 26. Minimum and Maximum Braking Efficiencies for 3-S2

4.5 Clearance Times

Figure 27 illustrates the signal clearance times required for an unloaded 3-S2 as a function of both its initial speed and the tire-pavement coefficient of friction. The diagram highlights the combinations of speed and coefficient of friction for which the clearance times calculated using the ITE standard for achievable deceleration could not be achieved. The diagram illustrates that the deceleration standard can only be achieved for the unloaded 3-S2 at coefficients of friction greater than about 0.7.

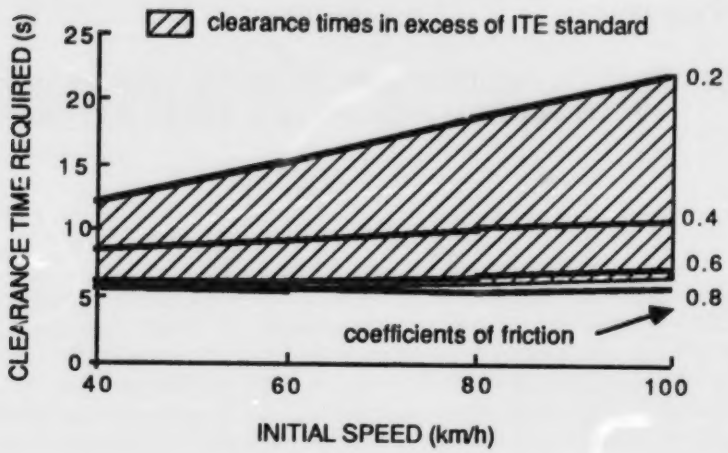


Figure 27. Required Clearance Times for an Unloaded 3-S2

CHAPTER 5

BRAKING CAPABILITIES OF TRACTOR SEMI-TRAILERS WITH TANDEM AND AIR-LIFT BELLY AXLES

5.1 Introduction

The vehicles analysed in this chapter are semi-trailers with tandem rear axles and are equipped with one or two air-lift belly axles which can be raised or lowered. It is assumed that these axles will only be deployed when the vehicles are carrying a full load because they decrease maneuverability and increase tire wear when lowered. To deal with the indeterminate nature of the equilibrium of vehicles with belly axles it has been assumed that when a fully loaded vehicle is operating with its belly axle down the air pressure on air-lift axles will be set such that the load carried will be at the maximum allowable of 10 000 kg.

5.2 Properties of the Tractor Semi-Trailer with Tandem and Belly Axles

Figure 28 illustrates the dimensions of the vehicle tested with the single belly axle while Table 8 summarizes its mass and dimension characteristics. When the belly axle is raised the characteristics are the same as those of the 3-S2 vehicle presented in Table 6, except that the tare weight of the semi-trailer is increased by 1 000 kg because of the additional axle it is carrying. The 3-S3/1B characteristics are based on information obtained about a vehicle used by a gravel carrier in the Toronto area.

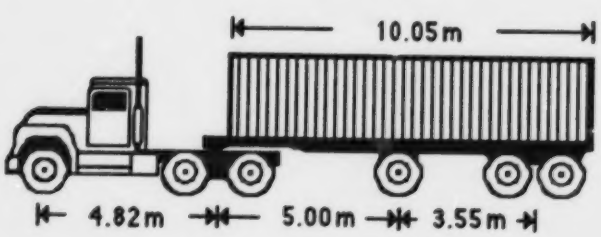


Figure 28. Dimensions of 3-S2/1B Tractor Semi-Trailer

Figure 29 illustrates the dimensions of the vehicle with two belly axles, and Table 9 lists its mass and dimensions characteristics. The properties of the 3-S4/2B were assembled from a Canroad test vehicle. The characteristics of the braking systems are the same as those presented in Table 7 for the 3-S2 vehicle, except that additional braking power is provided on the belly axles identical to that on the other semi-trailer axles.

These vehicles have been loaded with a typical heavy cargo (17 000 N/m^3) because the purpose of adding belly axles is to provide load capacity in a vehicle which "weighs out". Four load conditions were tested in both cases and these are:

1. fully loaded to the legal load limit for the configuration with axle(s) lowered and this means GVMs of 48 704 kg for the 3-S3/1B and 57 096 kg for the 3-S4/2B, respectively
2. fully loaded with the axles raised (illegal, but common in urban areas),

3. half unloaded from the top with the axle(s) raised and this means GVM's of 33 003 kg for the 3-S3/1B and 36 798 kg for the 3-S4/2B, and
4. unloaded.

Table 8. Mass and Dimension Properties of 3-S3/1B

Tractor - 3 axles	
mass (kg)	9 227
centre of mass height (m)	0.88
fifth wheel height (m)	1.22
front axle to c of m (m)	2.61
c of m to rear axle (m)	1.45
c of m to last axle (m)	2.98
c of m to fifth wheel (m)	1.76
Unloaded semi-trailer - tandem rear and 1 belly axle	
mass (kg)	8 074
length (m)	10.06
width (m)	2.50
king pin offset (m)	-0.50
leading edge to belly axle (m)	4.94
leading edge to rear axle (m)	7.58
leading edge to last axle (m)	9.41
leading edge to c of m (m)	5.74
c of m height (m)	1.27
height of loading bed (m)	1.37

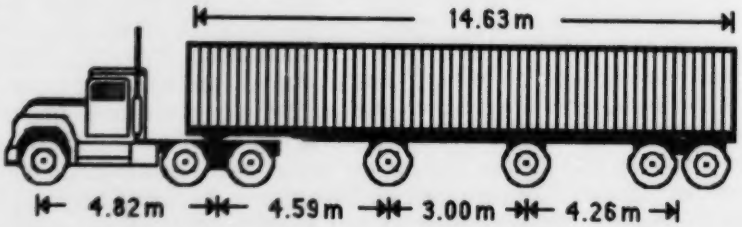


Figure 29. Dimensions of 3-S4/2B Tractor Semi-Trailer with Two Belly Axles

5.3 Braking Distances

Figure 30 illustrates the braking distances required to stop the 3-S3/1B from 80 km/h for four coefficients of friction under the four load conditions while Figure 31 illustrates the braking distances required to stop the 3-S4/2B. The current braking distance standard of 81 m for an 80 km/h design speed is also indicated on both diagrams.The diagrams illustrate that for the partially loaded and unloaded conditions the standard cannot be achieved for coefficients of friction of less than about 0.5.

At coefficients of friction about equal to those assumed in the geometric design standards, the unloaded vehicles require braking distances about twice as long as those specified in the standards and the fully and partially loaded vehicles about 1.4 times.

Table 9. Mass and Dimension Properties of 3-S4/2B

Tractor - 3 axles	
mass (kg)	8 200
centre of mass height (m)	0.88
fifth wheel height (m)	1.22
front axle to c of m (m)	2.41
c of m to rear axle (m)	1.65
c of m to last axle (m)	3.18
c of m to fifth wheel (m)	2.03
Unloaded semi-trailer - tandem rear and 2 belly axles	
mass (kg):	8 300
length (m):	14.63
width (m):	2.50
king pin offset (m):	0.91
leading edge to belly axle 1 (m):	6.00
leading edge to belly axle 2 (m):	9.00
leading edge to rear axle (m):	12.65
leading edge to last axle (m):	13.87
leading edge to c of m (m):	7.82
c of m height (m):	1.27
height of loading bed (m):	1.37

For the 3-S3/1B fully loaded with the axle up or down, premature lockup occurs at the front tandem except for coefficients of friction in the range of 0.6-0.8, where the braking is efficient enough for the deceleration to be limited instead by the amount of braking power available. When the 3-S4/2B is fully loaded with the axles up or down the premature lockup occurs at the rear tandem. The extra belly axle serves to take load off the rear tandem making it the underloaded axle group. With the axles up, the braking is efficient enough to allow the deceleration to be limited by the available braking power at coefficients of friction from 0.6-0.8. When the vehicles are half unloaded with the axle(s) up, the premature lockup occurs at either the front or the rear tandem, with braking being power limited only at a coefficient of friction of 0.8. When the vehicles are unloaded with their axle(s) up, the lockup is at the rear tandem in both cases for all speeds and coefficients of friction. The unloaded performance is the worst because the distribution of braking power was established for the load distribution of a fully loaded vehicle, making the rear tandem underloaded when the vehicles are empty.

Figures 32 and 33 illustrate the influence of initial speed on the braking distances required by the unloaded 3-S3/1B and 3-S4/2B vehicles with raised belly axles, respectively, over the range of coefficients of friction tested. The unloaded condition is examined in each case because it results in the worst performance for each vehicle, as is apparent from Figures 30 and 31. The hatched areas show the braking distances which are in excess of those specified in the geometric design standards. These vehicles can only achieve the RTAC standards for coefficients of friction greater than about 0.5, which is similar to the critical coefficient of friction observed with the 3-S2.

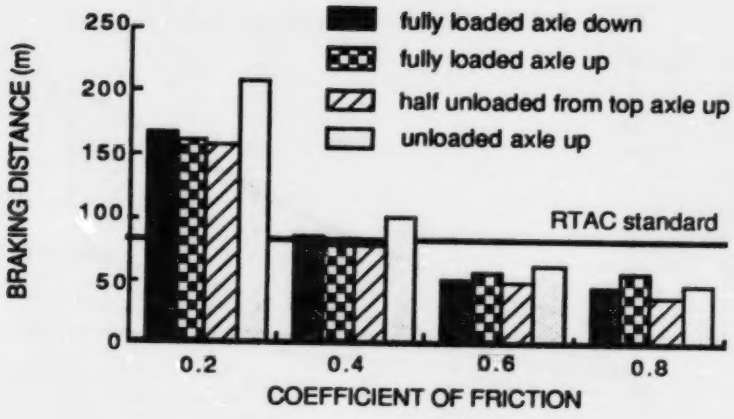


Figure 30. Braking Distances for 3-S3/1B from 80 km/h for Various Coefficients of Friction

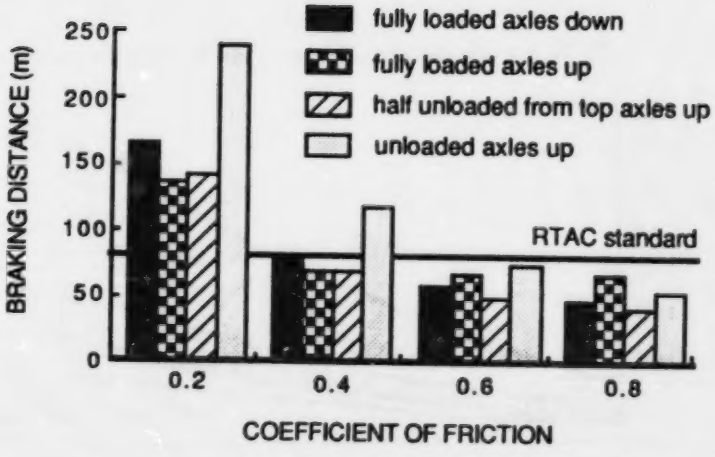


Figure 31. Braking Distances for 3-S4/2B from 80 km/h for Various Coefficients of Friction

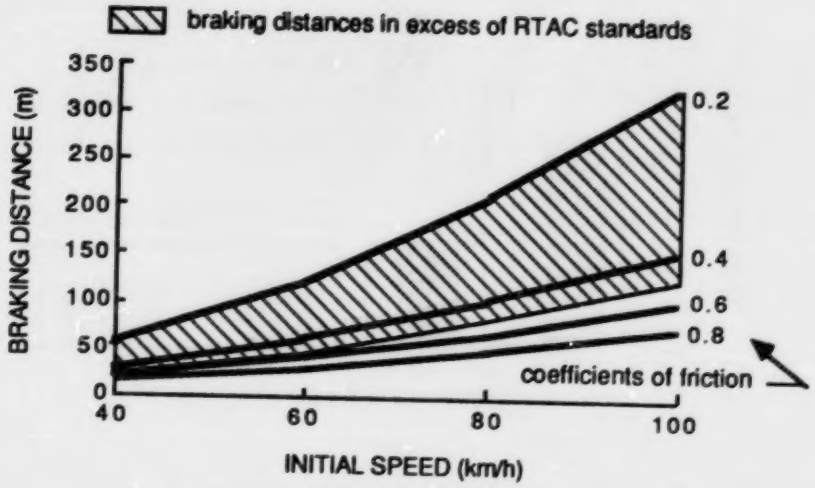


Figure 32. Braking Distances for Unloaded 3-S3/1B with Raised Belly Axle from Various Speeds

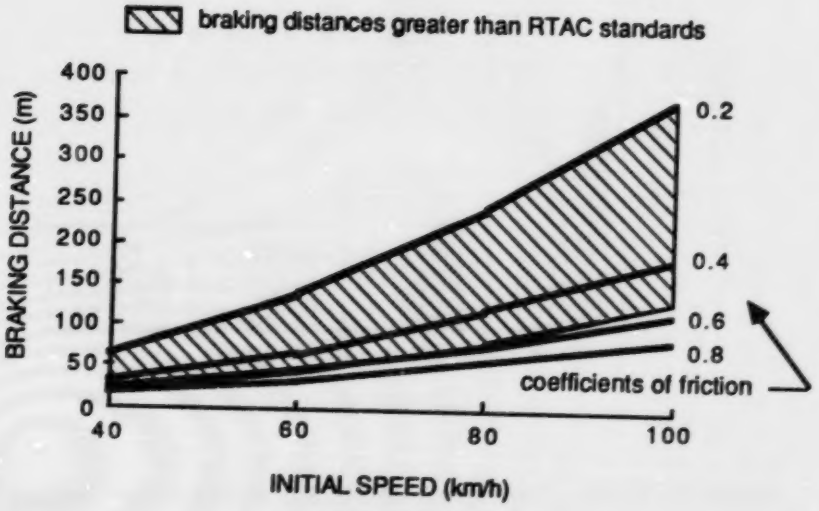


Figure 33. Braking Distances for Unloaded 3-S4/2B with Raised Belly Axles from Various Speeds

5.4 Braking Efficiencies

Figure 34 illustrates the maximum and minimum braking efficiencies of the 3-S3/1B for the four load conditions, and Figure 35 presents this information for the 3-S4/2B. The range of braking efficiencies reflects the changing coefficients of friction and speeds. The diagrams show that the proposed RTAC braking efficiency criterion of 70 percent is not achieved only when the vehicles are unloaded. These braking efficiencies are generally superior to those estimated for the 3-S2. The rear axles are slightly less underloaded when the semi-trailer is empty because they carry the additional weight of the retracted belly axles and this leads to a marginal improvement in the braking efficiency.

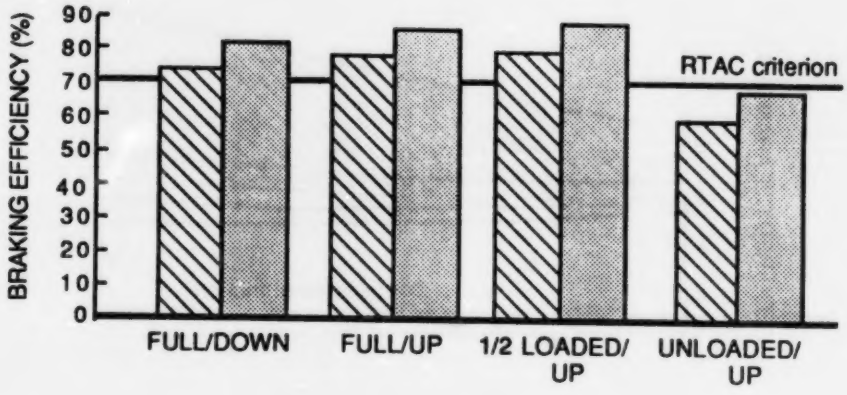


Figure 34. Minimum and Maximum Braking Efficiencies for 3-S3/1B

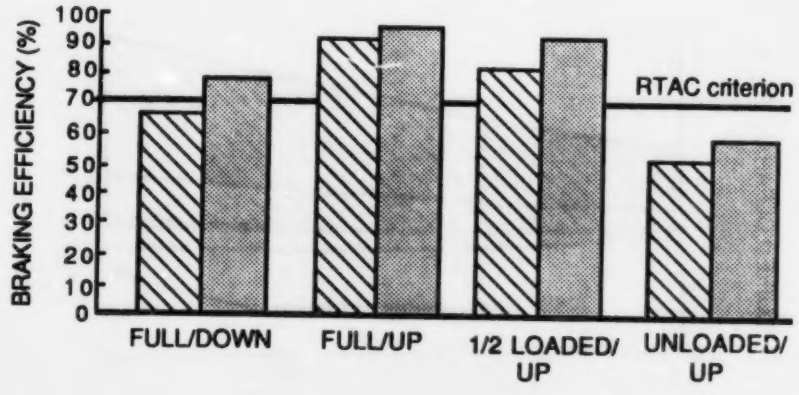


Figure 35. Minimum and Maximum Braking Efficiencies for a 3-S4/2B

5.6 Clearance Times

Figure 36 illustrates the signal clearance times required for the unloaded 3-S3/1B as a function of both its initial speed and the tire-pavement coefficient of friction. Figure 37 presents these results for the unloaded 3-S4/2B. The diagrams highlight the combinations of speed and coefficient of friction for which the clearance times calculated using the ITE standard for achievable deceleration could not be achieved. Both diagrams indicate that the clearance times calculated using ITE standards would be appropriate provided the coefficient of friction is greater than about 0.5. This critical coefficient of friction is similar to that identified for the straight trucks.

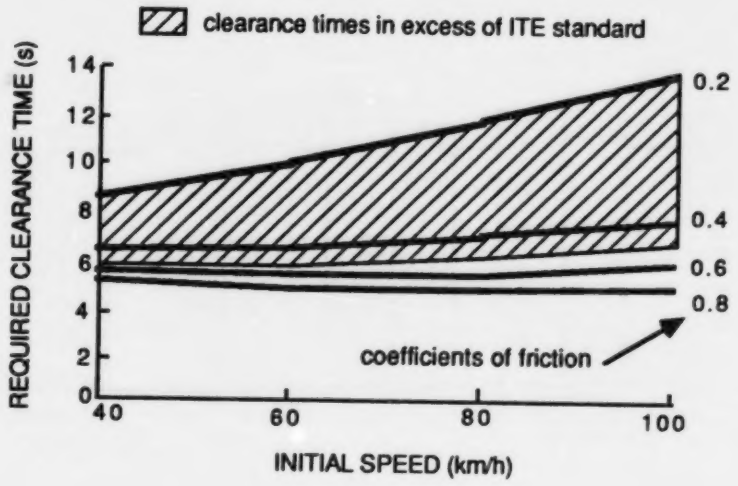


Figure 36. Clearance Times Required for Unloaded 3-S3/1B with Raised Belly Axle from Various Speeds

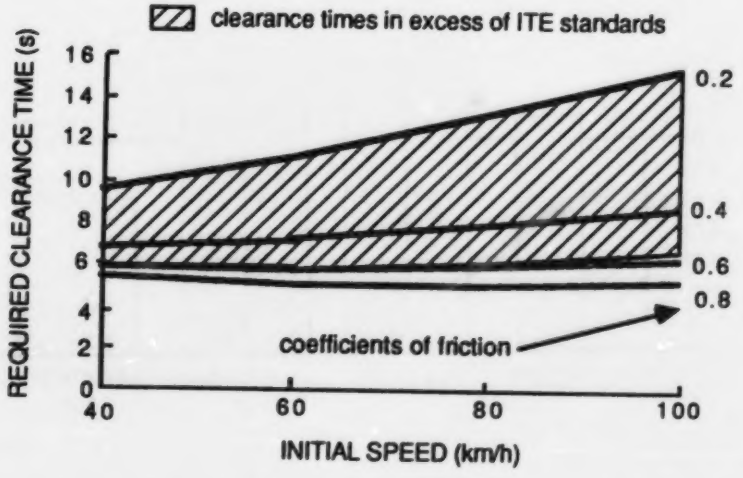


Figure 37. Clearance Times Required for an Unloaded 3-S4/2B with Raised Belly Axles from Various Speeds

CHAPTER 6

BRAKING CAPABILITIES OF TRACTOR SEMI-TRAILERS WITH TRIDEM AND AIR-LIFT BELLY AXLES

6.1 Introduction

The vehicles analysed in this chapter are tractor semi-trailers with a tridem axle group and either one or two belly axles. It is assumed that the air-lift axles will only be lowered when the vehicle is carrying a full load.

6.2 Properties of the Tractor Semi-Trailer with a Tridem and Belly Axles

Table 10 summarizes the mass and dimension characteristics of the vehicle with one lowered belly axle, and Table 11 those of the vehicle with two lowered belly axles analysed in these braking studies. When the belly axles are raised the dimensional characteristics become those of a tractor semi-trailer with a tridem. The mass of the vehicles remain unchanged because the additional axles are still attached. The properties of the 3-S4/1B and the 3-S5/2B were assembled from Canroad test vehicles. The characteristics of the braking systems are the same as those presented in Table 7 for the 3-S2 vehicle, except that there is additional braking power on the belly axles identical to that on the other semi-trailer axles. Figure 38 illustrates the configuration of the belly-axled tridem vehicles analysed in this study.

Table 10. Mass and Dimension Properties of 3-S4/1B

Tractor - 3 axles	
same as Table 6 for 3-S2 tractor	
Unloaded semi-trailer - 2 axles and 1 belly axle	
mass (kg)	8 300
length (m)	14.63
width (m)	2.50
king pin set back (m)	0.91
leading edge to belly axle (m)	5.49
leading edge to rear axle (m)	11.43
leading edge to last axle (m)	13.87
leading edge to c of m (m)	7.40
c of m height (m)	1.27
height of loading bed (m)	1.37

These vehicles have been loaded with a typical heavy cargo (17 000 N/m^3) because the purpose for adding the belly axle is to provide load capacity in a vehicle which "weighs out". Four load conditions were tested in both cases and these are:

A. fully loaded to the legal load limit with axle(s) lowered which means GVM's of 53 290 kg for the 3-S4/1B and 56 828 kg for the 3-S5/2B,
B. fully loaded with the axles raised (illegal, but common in urban areas),
C. half unloaded from the top with the axle(s) raised which means GVM's of 34 895 kg for the 3-S4/1B and 37 163 for the 3-S5/2B, and
D. unloaded.

Table 11. Mass and Dimension Properties of 3-S5/2B

Tractor - 3 axles	
same as Table 6 for 3-S2 tractor	
Unloaded semi-trailer - 2 axles and 2 bellies	
mass (kg)	9 300
length (m)	14.63
width (m)	2.50
king pin set back (m)	0.91
leading edge to belly axle 1 (m)	5.50
leading edge to belly axle 2 (m)	8.50
leading edge to rear axle (m)	11.43
leading edge to last axle (m)	13.87
leading edge to c of m (m)	5.74
c of m height (m)	1.27
height of loading bed (m)	1.37

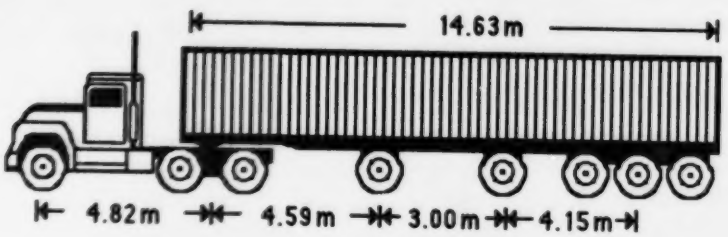


Figure 38. Dimensions of 3-S4/1B and 3-S5/2B Vehicles

6.3 Braking Distances

Figure 39 illustrates the braking distances required to stop the 3-S4/1B from 80 km/h for four coefficients of friction under the four load conditions while Figure 40 illustrates the braking distances required by the 3-S5/2B. The current braking distance standard of 81 m for an 80 km/h design speed is also indicated on both diagrams. The diagrams illustrate in each case that for the loaded and partially loaded conditions the standard cannot be achieved for coefficients of friction of less than about 0.5. For the unloaded condition with both vehicle types the standard cannot be achieved for coefficients less than about 0.8.

At coefficients of friction about equal to those assumed in the geometric design standards the unloaded vehicles require braking distances about three times as long as those specified in the standards and the fully and partially loaded vehicles about 1.8 times.

For the 3-S4/1B and 3-S5/2B vehicles fully loaded with the axle(s) down, premature lockup occurs at the tridem. For the fully loaded condition with the axle raised, the premature lockup again occurs at the tridem, but for coefficients of friction greater than 0.6 the deceleration is limited by the available brake power. When the belly axle is down it serves to take load off of the tridem making it more underloaded than when the axle is raised. When the vehicles are half or completely unloaded with the axle(s) up, the premature lockup occurs at the tridem. The unloaded performance is the poorest because the distribution of braking power was established for the load distribution of a fully loaded vehicle making the tridem more underloaded when

the vehicles are empty.

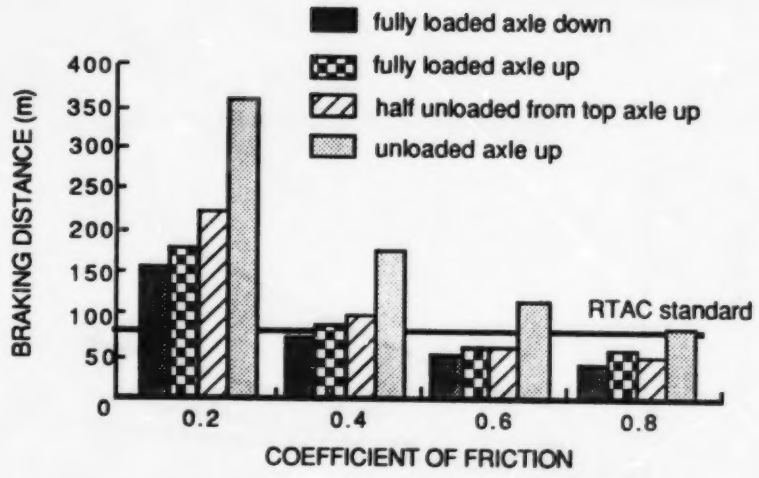


Figure 39. Braking Distances for a 3-S4/1B from 80 km/h for Various Coefficients of Friction

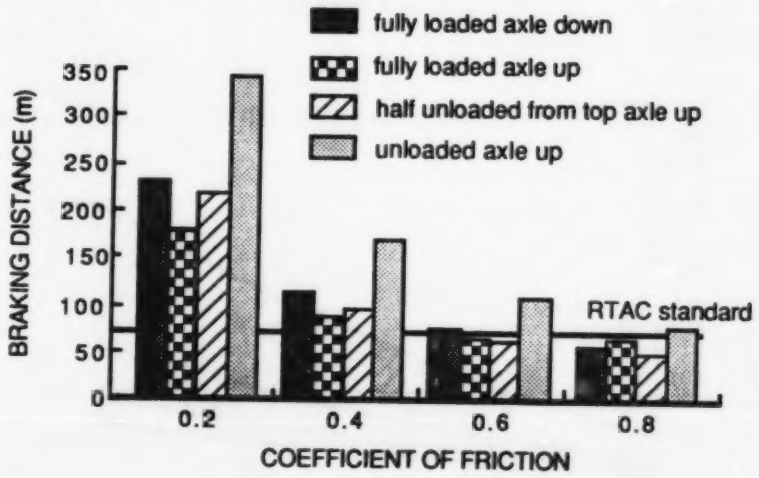


Figure 40. Braking Distances for a 3-S5/2B from 80 km/h for Various Coefficients of Friction

Figures 41 and 42 illustrate the influence of initial speed on the braking distances required by the unloaded 3-S4/1B and 3-S5/2B vehicles with raised belly axles, respectively, over the range of coefficients of friction tested. The unloaded condition is examined in each case because it results in the worst performance for each vehicle, illustrated in Figures 39 and 40. The hatched areas show the braking distances which are in excess of those specified in the geometric design standards. These vehicles cannot

achieve the RTAC standards over the range of coefficients of friction tested. Note that the unloaded tridem-axled vehicle exhibits poorer braking performance than the unloaded tandem-axled vehicles examined in previous chapters. Because the tridem has 1.5 times the braking power of a tandem it is more severely overbraked in the unloaded condition.

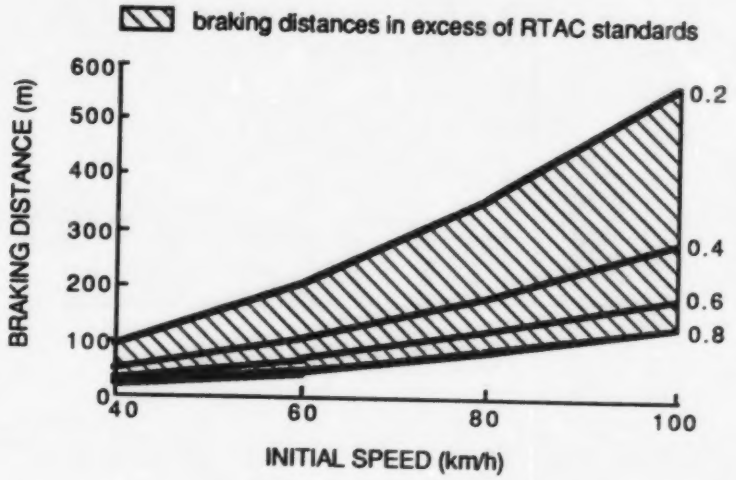


Figure 41. Braking Distances for an Unloaded 3-S4/1B with Raised Belly Axle from Various Speeds

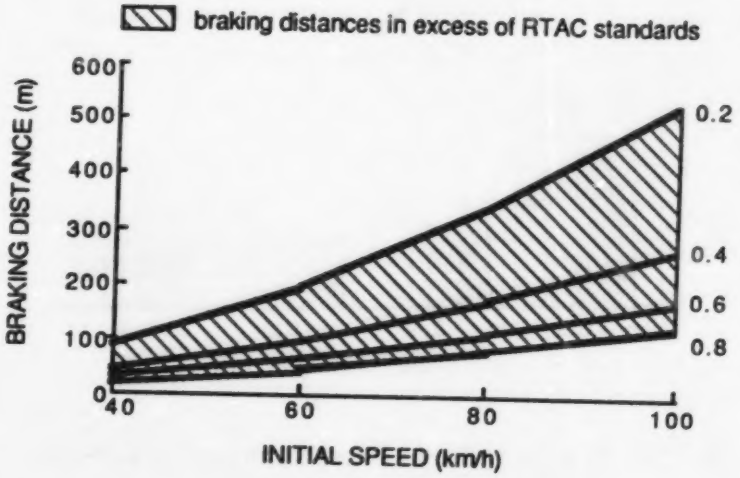


Figure 42. Braking Distances for an Unloaded 3-S5/2B with Raised Belly Axles from Various Speeds

6.4 Braking Efficiencies

Figure 43 illustrates the maximum and minimum braking efficiencies of the 3-S4/1B for the four load conditions and Figure 44 presents this information for the 3-S5/2B.

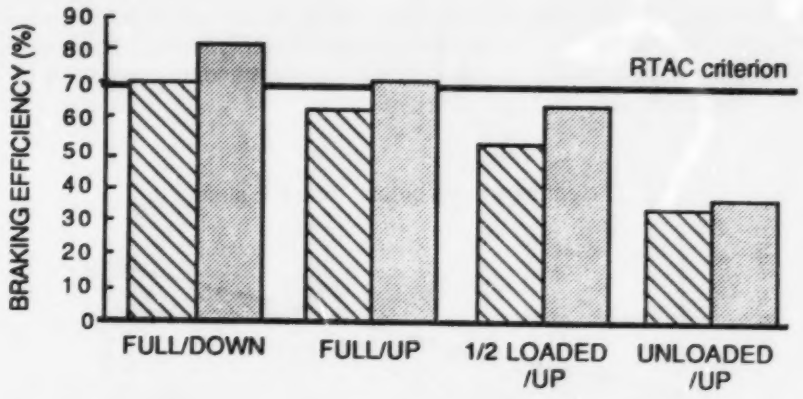


Figure 43. Minimum and Maximum Braking Efficiencies for a 3-S4/1B

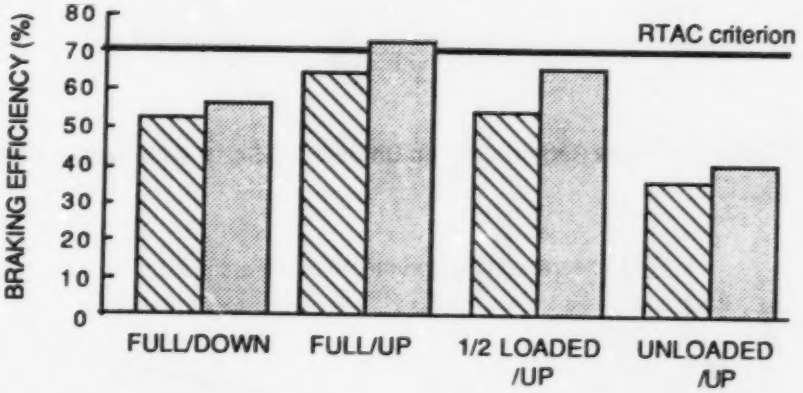


Figure 44. Minimum and Maximum Braking Efficiencies for a 3-S5/2B

The diagrams also indicate that the proposed RTAC braking efficiency criterion of 70 percent. Figure 43 indicates the braking is most efficient when the 3-S4/1B is fully loaded with the axle lowered and that the criterion is also achieved when the vehicle is fully loaded with the axle raised. Figure 44 illustrates that the criterion is achieved by the fully loaded 3-S5/2B with its axles raised but not achieved by the partially and completely unloaded vehicles. Note, however, that the braking for the fully loaded condition with the axles down is much less efficient than the corresponding load condition for the 3-S4/1B. This is not surprising. The two vehicles are very similar with axles up, so the efficiencies are similar. With two belly axles, the 3-S5/2B carries less load on the tridem than the 3-S4/1B resulting in the tridem being more underloaded with respect to the tridem's braking power with two belly axles deployed. Again, note that in the unloaded condition braking efficiency is reduced because the unloaded tridem is severely overbraked.

6.5 Clearance Times

Figure 45 illustrates the signal clearance times required for the unloaded 3-S4/1B as a function of both its initial speed and the tire-pavement coefficient of friction. Figure 46 presents these results for the unloaded 3-S5/2B. The diagrams highlight the combinations of speed and coefficient of friction for which the clearance times calculated using the ITE standard for achievable deceleration could not be achieved. Both diagrams indicate that the clearance times calculated using ITE standards could only be achieved with a coefficient of friction of about 0.8.

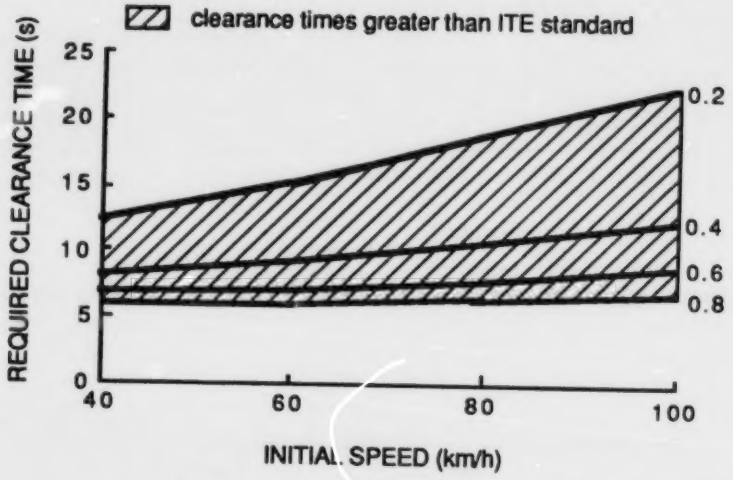


Figure 45. Clearance Times Required for an Unloaded 3-S4/1B with Raised Belly Axle

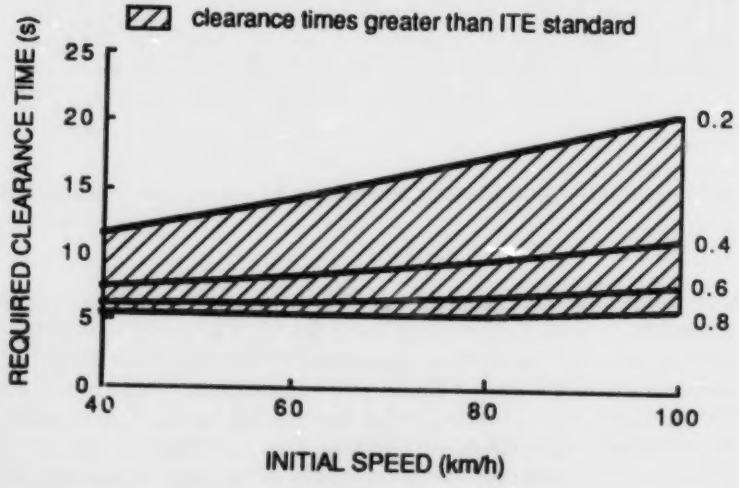


Figure 46. Clearance Times Required for an Unloaded 3-S5/2B with Raised Belly Axles

CHAPTER 7

BRAKING CAPABILITIES OF DOUBLE TRAILER COMBINATION VEHICLES

7.1 Introduction

This chapter analyses the braking characteristics of two tractor double trailers, where the first of the two trailers is a semi-trailer in each case. Two configurations for the second trailer have been examined with the first being an A-train and the second a B-train. The first case is a 3-S1-2, which means that the second trailer is attached to the first through an A-train connection. A one-axled converter dolly is used at the rear of the first semi-trailer to act as a base for the attachment of the second semi-trailer. This 3-S1-2 is modelled as a tractor and three semi-trailers. The converter dolly is modelled as the second of these semi-trailers because it has the general characteristics of a semi-trailer. The rear semi-trailer transfers vertical and horizontal forces to it and it in turn transfers vertical and horizontal forces to the front semi-trailer (5).

Two B-trains are analysed and these are a 3-S2-S2 and a 3-S3-S2. The B-train connection uses an extension to the rear of the first semi-trailer to act as the base for the second semi-trailer. These vehicles are modelled as a tractor and two semi-trailers with the last transferring vertical and horizontal loads to the first through the fifth wheel.

7.2 Properties of the A-train Double

Figure 47 illustrates the dimensions of the 3-S1-2 and Table 12 summarizes its detailed mass and dimension characteristics. The properties were assembled from Canroad test vehicles. The characteristics of the braking systems are the same as those presented in Table 7 for the 3-S2 vehicle, except that additional braking power is provided on all semi-trailer and converter dolly axles identical to that on the other semi-trailer axles.

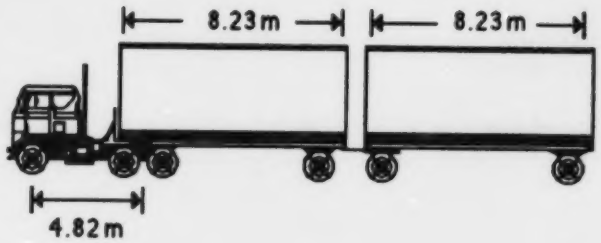


Figure 47. Dimensions of 3-S1-2 A-Train Double

These vehicles have been loaded with a medium-density cargo (5 000 N/m^3) because the purpose of double trailers is to provide both space and weight capacity. Three load conditions were tested and these are:

A. both trailers fully loaded to the legal limit and this means a GVM of 46 343 kg,
B. rear trailer unloaded with the first remaining fully loaded and this means a GVM of 31 022 kg, and
C. both trailers unloaded.

Table 12. Mass and Dimension Properties of 3-S1-2

Tractor - 3 axles	
mass (kg)	8 300
centre of mass height (m)	0.88
fifth wheel height (m)	1.22
front axle to c of m (m)	2.41
c of m to rear axle (m)	1.65
c of m to last axle (m)	3.18
c of m to fifth wheel (m)	2.03
First unloaded semi-trailer - 1 axle	
mass (kg)	3 200
length (m)	8.23
width (m)	2.50
king pin offset (m)	0.61
leading edge to axle (m)	7.47
leading edge to c of m (m)	4.15
c of m height (m)	1.27
height of loading bed (m)	1.37
Converter Dolly - 1 axle	
mass (kg)	1 000
pivot to axle (m)	1.83
pivot to c of m (m)	1.60
c of m height (m)	0.80
pivot to rear pivot (m)	1.83
Last unloaded semi-trailer - 1 axle	
mass (kg)	3 200
length (m)	8.23
width (m)	2.50
king pin offset (m)	0.61
leading edge to axle (m)	7.47
leading edge to c of m (m)	4.15
c of m height (m)	1.27
height of loading bed (m)	1.37

Braking Distances

Figure 48 illustrates the braking distances required to stop the 3-S1-2 from 80 km/h for four coefficients of friction under the four load conditions. The current braking distance standard of 81 m for an 80 km/h design speed is also indicated on the diagrams. The diagram illustrates that for the fully loaded condition, the braking distance standard can be achieved for coefficients of friction greater than about 0.5. For the unloaded condition, the standard can be achieved for coefficients greater than about 0.7. For the empty rear-trailer condition, the standard is not achieved for any coefficient of friction tested.

Effects of Speed

Figure 49 illustrates the impacts of speed on the braking distances required by the 3-S2-S2 with the rear trailer empty, which produced the longest braking distances in Figure 48. The diagram indicates that the RTAC braking standards are not achieved for any of the tire-pavement frictions tested. Very long braking distances are required for the wet and icy pavement conditions.

Figure 48. Braking Distances for 3-S1-2 from 80 km/h for Various Coefficients of Friction

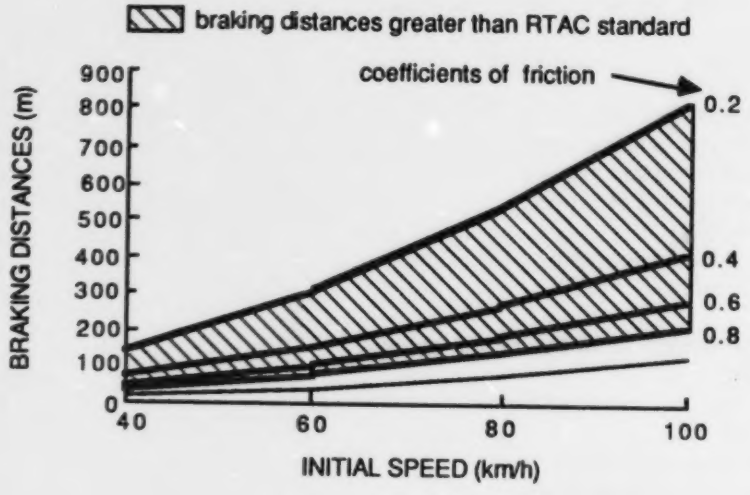


Figure 49. Braking Distances for 3-S1-2 with Rear Trailer Empty from Various Speeds

7.3 Properties of the B-Trains

Figure 50 shows the dimensions of the 3-S2-S2 and 3-S3-S2 B-trains analysed in this study while Tables 13 and 14 list their detailed mass and dimension properties. The brake system is the same as that used previously and the loading conditions used are :

1. fully loaded which results in a GVM of 50 402 kg for the 3-S2-S2 and 57 289 kg for the 3-S3-S2,
2. partially loaded which results in a GVM of 34 451 kg for the 3-S2-S2 and 38 294 kg for the 3-S3-S2 , and
3. unloaded.

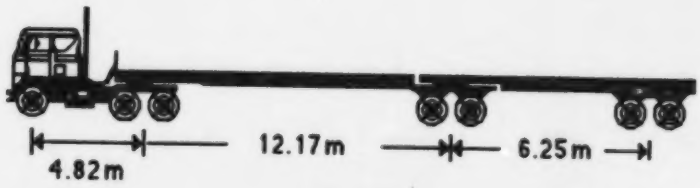


Figure 50. Dimensions of 3-S2-S2 and 3-S3-S2 B-Trains

Table 13. Mass and Dimension Properties of 3-S2-S2

Tractor - 3 axles	
same as Table 10	
First unloaded semi-trailer - 2 axles	
mass (kg)	6 000
length (m)	8.23
width (m)	2.50
king pin set back (m)	1.52
leading edge to rear axle (m)	8.64
leading edge to last axle (m)	9.86
leading edge to c of m (m)	5.38
c of m height (m)	1.27
height of loading bed (m)	1.37
pivot to rear pivot (m)	8.33
Last unloaded semi-trailer - 2 axles	
mass (kg)	4 300
length (m)	8.23
Width (m)	2.50
leading edge to pivot (m)	0.61
leading edge to rear axle (m)	6.25
leading edge to last axle (m)	7.47
leading edge to c of m (m)	4.15
c of m height (m)	1.27
height of loading bed (m)	1.37

Table 14. Mass and Dimension Properties of 3-S3-S2

Tractor - 3 axles	
same as Table 10	
First unloaded semi-trailer - 3 axles	
mass (kg)	6 800
length (m)	8.23
width (m)	2.50
leading edge to pivot (m)	1.52
leading edge to rear axle (m)	7.42
leading edge to last axle (m)	9.86
leading edge to c of m (m)	5.08
c of m height (m)	1.27
height of loading bed (m)	1.37
pivot to rear pivot (m)	8.33
Last unloaded semi-trailer - 2 axles	
mass (kg)	4 300
length (m)	8.23
width (m)	2.50
leading edge to pivot (m)	0.61
leading edge to rear axle (m)	6.25
leading edge to last axle (m)	7.47
leading edge to c of m (m)	4.15
c of m height (m)	1.27
height of loading bed (m)	1.37

Braking Distances

Figure 51 illustrates the braking distances required to stop the 3-S2-S2 from 80 km/h for four coefficients of friction under the four load conditions while Figures 52 illustrates the braking distances required by the 3-S3-S2 double trailer.The diagrams illustrate in each case that for the fully loaded condition the braking distance standard can be achieved for coefficients of friction greater than about 0.5. For the unloaded condition, the standard can be achieved for coefficients greater than about 0.7. For the empty rear trailer condition, the standard is not achieved for any coefficient of friction tested. The most striking feature of these diagrams is their similarity. The lower braking of the single axle compared to the tandem axle, together with the lower load carried by the single axle compared to the tandem because of the lower weight of the trailer, has resulted in the single- and tandem-axled trailers displaying similar braking performances.

At coefficients of friction about equal to those assumed in the geometric design standards, the vehicles with the rear trailer empty require braking distances about five times as long as those specified in the standards, those with both trailers empty about 2.5 times, and the fully loaded vehicles about 1.5 times.

For all of the vehicle types and load conditions premature lockup occurred at the rear tandem for the B-train doubles and at the rear axle for the A-train doubles. The only exception is the fully loaded 3-S1-2, which experienced premature lockup at the tractor tandem. This is not surprising as the 3-S1-2 has no tandem axles on its trailers. The braking power for the single axle is only half that for the tandems on the B-train doubles. The tandem axles tend more towards lockup because their braking power is higher relative to the load carried.

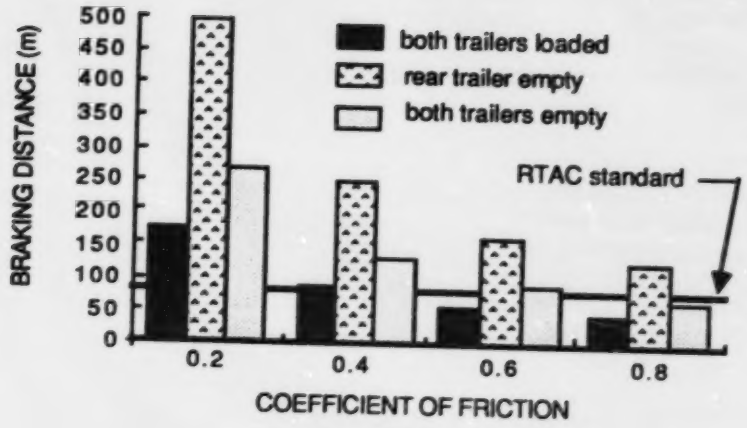


Figure 51. Braking Distances for 3-S2-S2 from 80 km/h for Various Coefficients of Friction

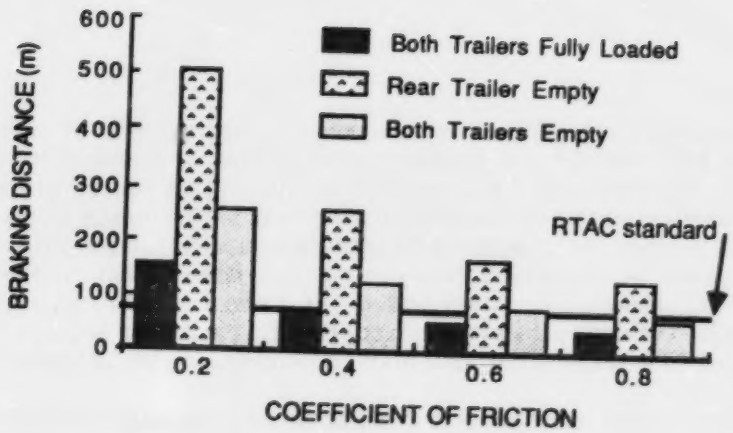


Figure 52. Braking Distances for 3-S3-S2 from 80 km/h for Various Coefficients of Friction

Effects of Speed

Figures 53 and 54 illustrate the influence of initial speed on the braking distances required by the 3-S2-S2 and 3-S3-S2 doubles, respectively, with the rear trailer empty over the range of coefficients of friction tested. This load condition is examined in each case because it results in the worst performance for each vehicle. The hatched areas show the braking distances which are in excess of those specified in the geometric design standards. These vehicles cannot achieve the RTAC standards over the range of coefficients of friction tested. In reviewing these results it should be remembered that the criterion limiting vehicle deceleration is the deceleration achieved at the level of braking where an axle lockup is imminent.

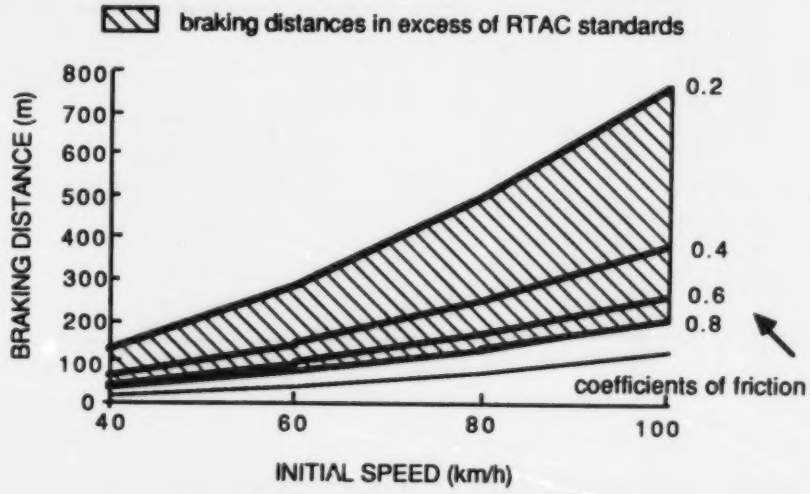


Figure 53. Braking Distances for 3-S2-S2 with Rear Trailer Empty from Various Initial Speeds

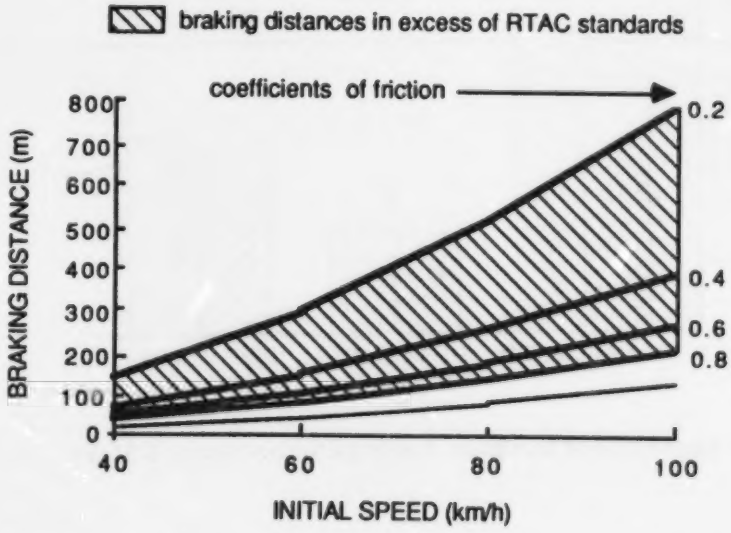


Figure 54. Braking Distances for 3-S3-S2 with Rear Trailer Empty from Various Initial Speeds

7.4 Braking Efficiencies

Figure 55 illustrates the maximum and minimum braking efficiencies of the 3-S1-2 for the three load conditions, Figure 56 for the 3-S2-S2, and Figure 57 for the 3-S3-S2. The diagrams also indicate the proposed RTAC braking efficiency criterion of 70 percent. These diagrams illustrate that only when the doubles have both trailers fully loaded are they capable of achieving this criterion.

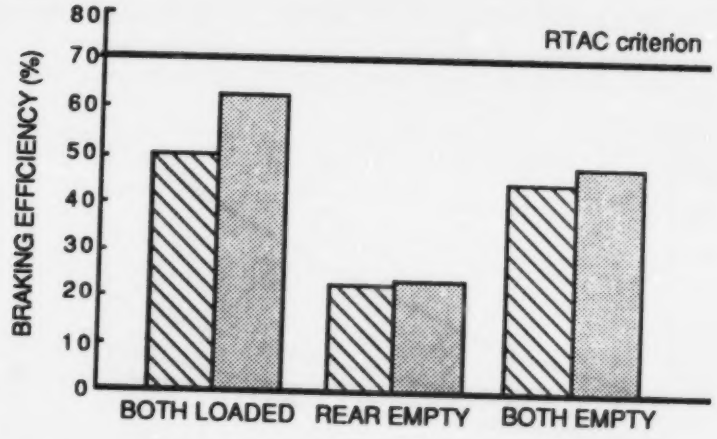


Figure 55. Minimum and Maximum Braking Efficiencies for a 3-S1-2

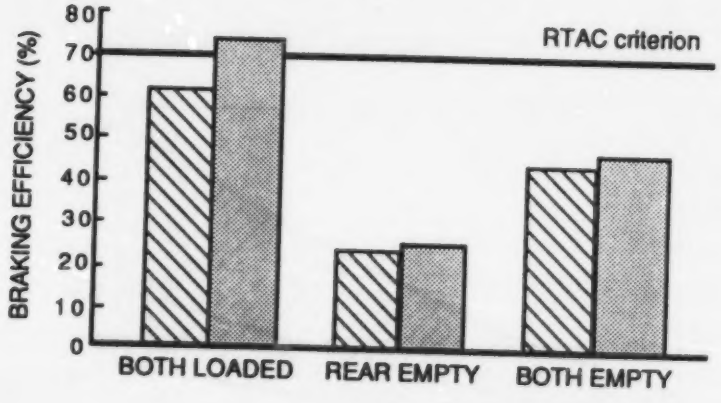


Figure 56. Minimum and Maximum Braking Efficiencies for 3-S2-S2

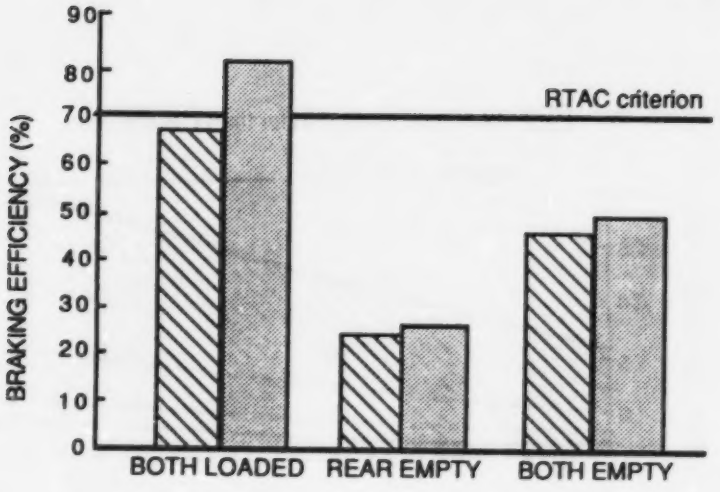


Figure 57. Minimum and Maximum Braking Efficiencies for 3-S3-S2

7.5 Clearance Times

Figure 58 illustrates the signal clearance times required for the 3-S1-2 with the rear trailer empty as a function of both its initial speed and the tire-pavement coefficient of friction. Figures 59 and 60 present these results for the 3-S2-S2 and 3-S3-S2, respectively, under the same load condition. The diagrams highlight the combinations of speed and coefficient of friction for which the clearance times calculated using the ITE standard for achievable deceleration could not be achieved. Both diagrams indicate that the clearance times calculated using ITE standards could not be achieved under any of the conditions of initial speed and friction tested. Once again, it should be recalled that the maximum deceleration is limited by the deceleration that can be achieved as the first axle locks up.

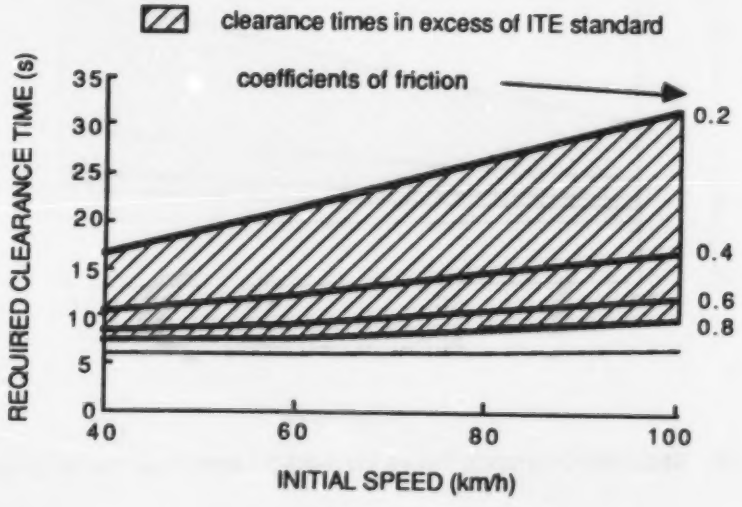


Figure 58. Required Clearance Times for 3-S1-2 with Rear Trailer Empty

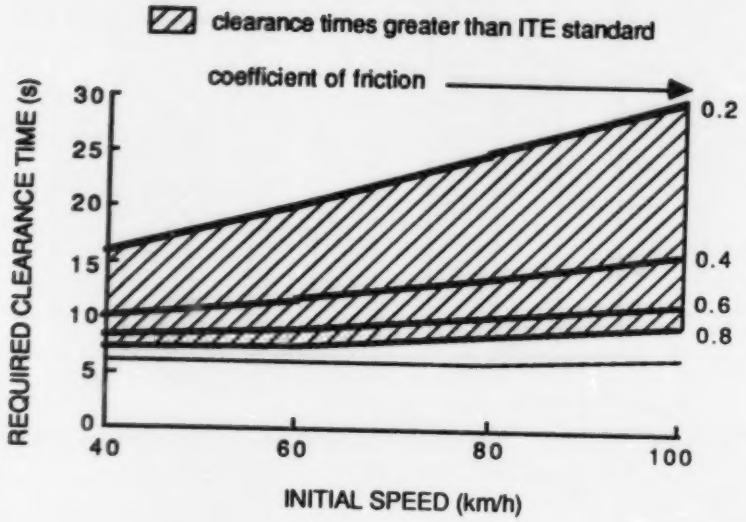


Figure 59. Required Clearance Times for 3-S2-S2 with Rear Trailer Empty

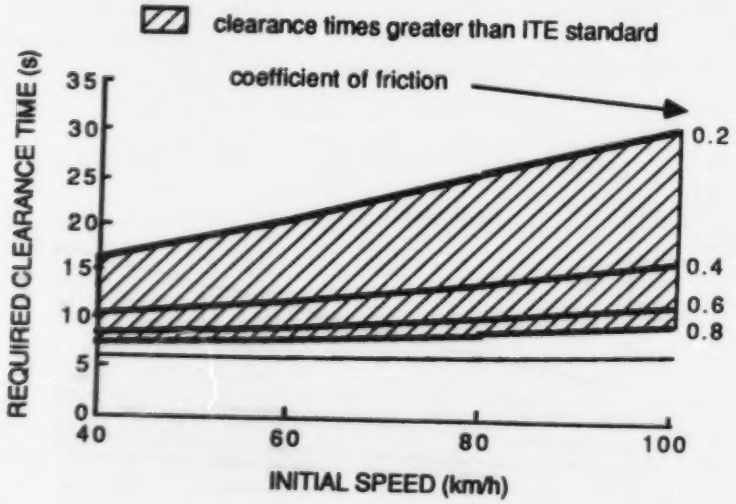


Figure 60. Required Clearance Times for 3-S3-S2 with Rear Trailer Empty

CHAPTER 8

BRAKING DISTANCE SUMMARY FOR DIFFERENT TRUCK TYPES

8.1 Braking Distances

This chapter compares the braking distances estimated for each of the heavy trucks and combination vehicles in the previous chapters. Table 15 summarizes the variations in the braking distance required to make a controlled stop with the mass, dimension, and brake system characteristics assumed for this study. The comparison is made between all of the vehicle types and load conditions tested. For the sake of clarity of presentation the results shown are restricted to those obtained for a speed of 80 km/h and for tire-road friction coefficients of 0.2 and 0.6 which are representative of poor and good road conditions.

Table 15. Braking Distances from 80 km/h

entries in metres

Truck Types	Coefficient of friction 0.2 Load Conditions				0.6 Load Conditions			
	FL	HL	U		FL	HL	U	
2-axle	140	161	155		66	69	60	
3-axle	155	155	187		60	62	64	
	FL	HL	U	BT	FL	HL	U	BT
3-S2	189	306	357	274	57	94	91	96
	FL/D	FL/U	HL/U	U/U	FL/D	FL/U	HL/U	U/U
3-S3/1B	166	161	157	208	51	57	50	64
3-S4/1B	160	184	227	362	55	66	65	120
3-S4/2B	165	137	141	238	58	67	49	74
3-S5/2B	231	180	218	342	76	66	65	111
	BF	RE	BE		BF	RE	BE	
3-S1-2	205	532	270		77	178	90	
3-S2-S2	179	498	268		61	167	90	
3-S3-S2	157	510	258		56	170	86	

Load Conditions:
- FL- Fully loaded to the legal limit
- HL- Half unloaded from the fully loaded condition
- U- Unloaded
- BT- Bobtail tractor
- /D- Belly axles down
- /U- Belly axles up
- BF- Both trailers fully loaded to the legal limit
- RE- Rear trailer unloaded with the front trailer remaining fully loaded
- BE- Both trailers unloaded

Figure 61 summarizes the braking distance data for each of the truck types for the two tire-pavement coefficients of friction for the fully-loaded condition. It should be recalled that the RTAC Geometric Design Standards specify a braking distance of 81 m from 80 km/h and that this braking distance is calculated for a coefficient of friction of 0.31 and an assumption of 100 percent braking efficiency.

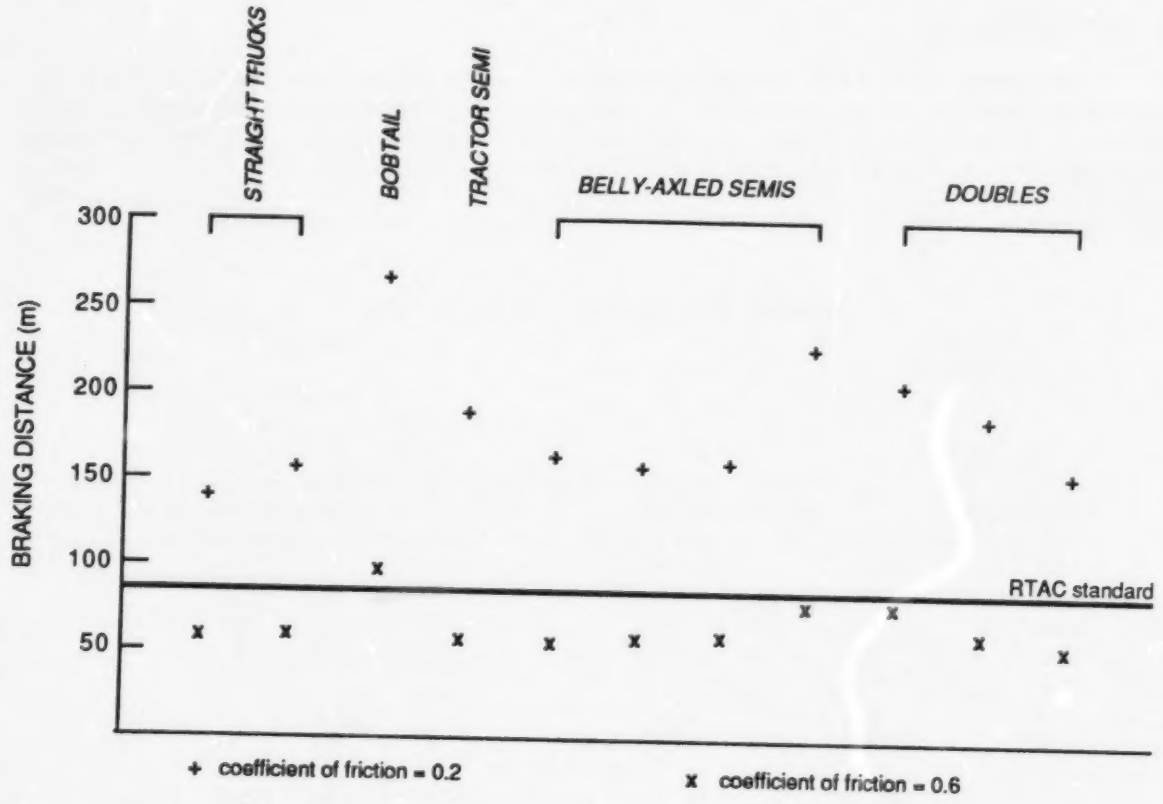


Figure 61. Braking Distances Required by Fully-Loaded Trucks for Two Tire-Pavement Coefficients of Friction

The diagram shows that the braking distances required by all truck types are lower than the RTAC standard for 80 km/h for the higher coefficient of friction, except for the bobtail tractor. There is modest variation in the braking distances required by the various vehicle types for the dry pavement condition, where the range is from about 50 m to 75 m. The braking capabilities of the trucks deteriorates substantially under the poor pavement conditions and this lower skid resistance tends to magnify the differences in braking capabilities between truck types. The braking distance required by the bobtail tractor increased to about 270 m.

Figure 62 shows the braking distances for the partially loaded vehicles for the two pavement conditions. The lower part of the diagram shows that the unloaded tractor semi-trailer and the double trailers exceed the RTAC standards even at the higher coefficient of friction. This behaviour reflects the deterioration in braking efficiency that occurs when the distribution of normal loads on the axles deviates from the distribution of braking forces which is particularly severe for the partially loaded condition. The degradation in braking capabilities is magnified very strongly for the partially loaded condition under the poorer pavement conditions. The increases in braking distances required by the tractor semi-trailer and the A- and B-train doubles should be noted.

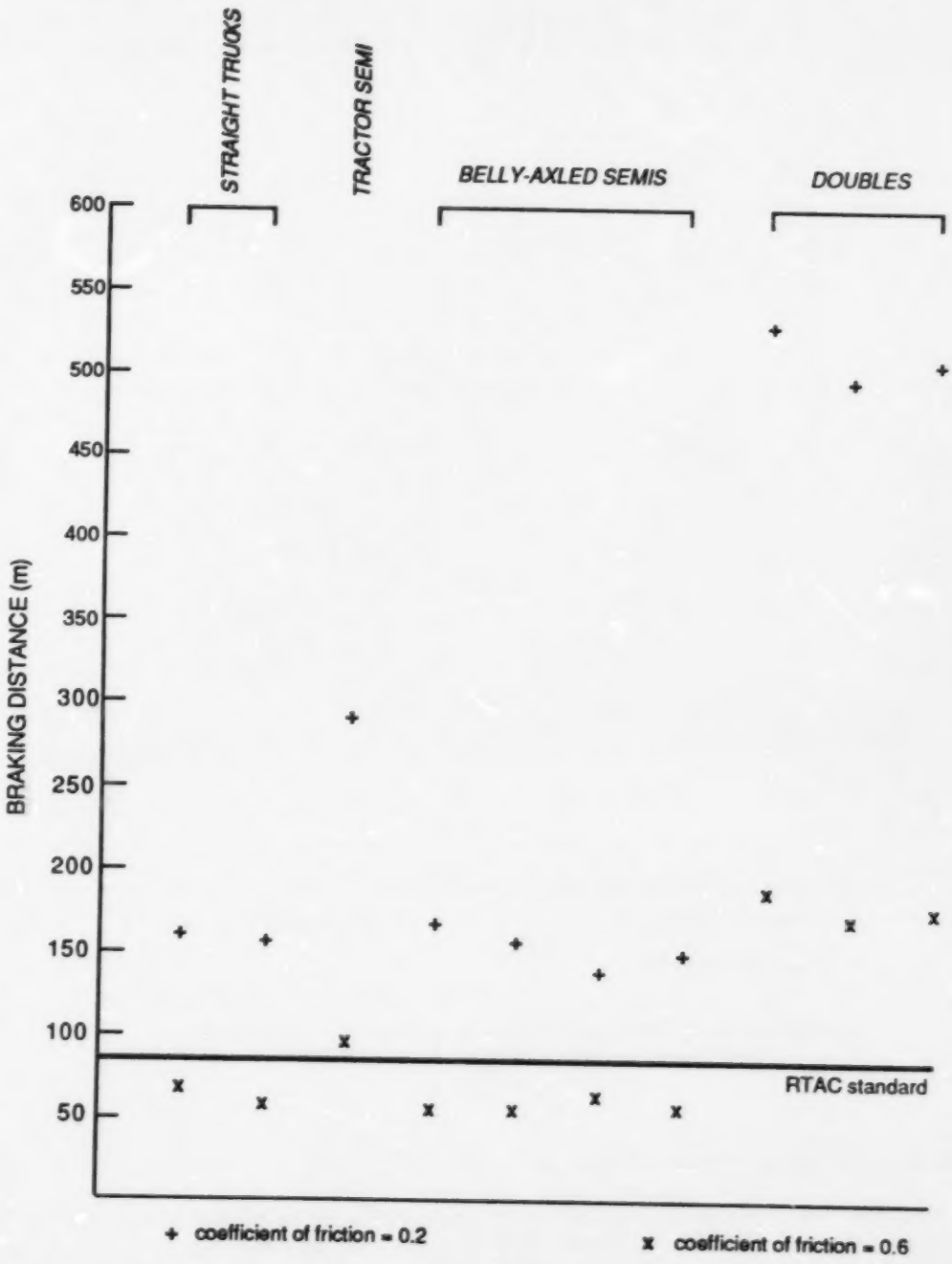


Figure 62. Braking Distances Required by Half Loaded Trucks for Two Tire-Pavement Coefficients of Friction

Figure 63 summarizes the braking distances required by the various truck types for the unloaded condition under the two coefficients of tire-pavement friction. Similar patterns in braking behaviour are illustrated with the tractor semi-trailer and the double trailers performing very poorly under the wet to icy pavement conditions. The diagram also shows the poor behaviour of the belly-axled semi-trailers when their belly axles are retracted.

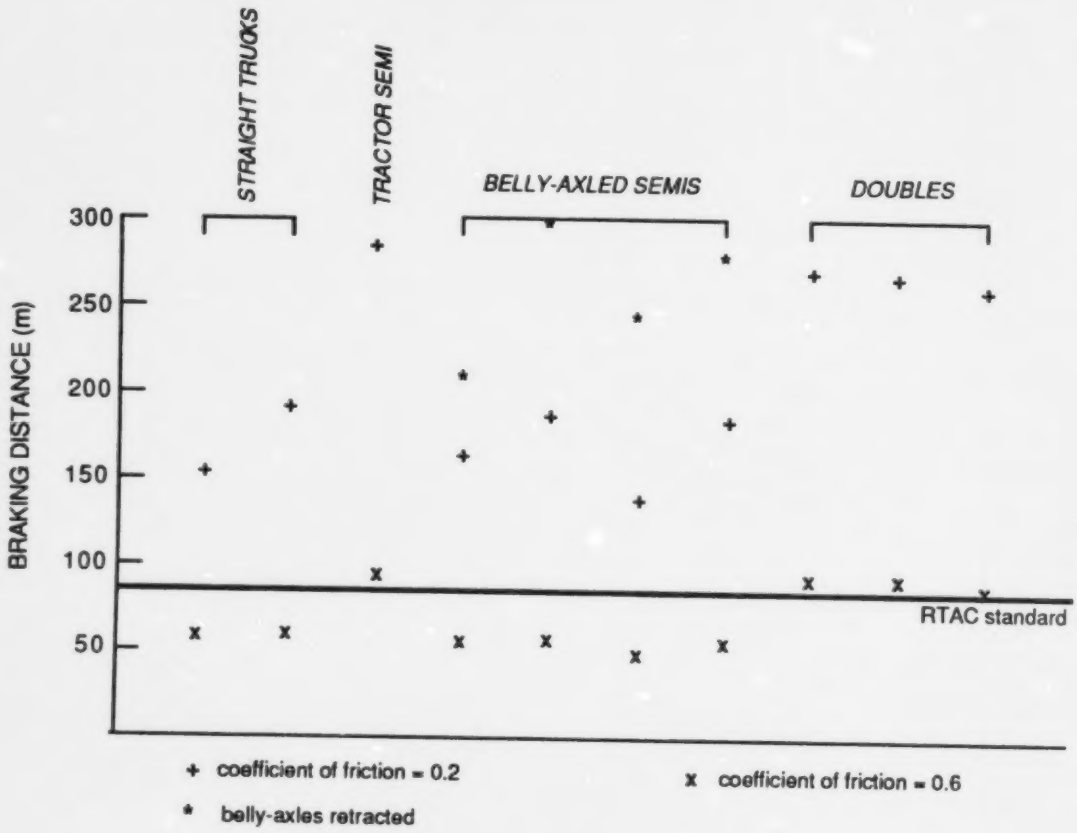


Figure 63. Braking Distances Required by Unloaded Trucks for Two Tire-Pavement Coefficients of Friction

8.2 Comparison with Braking Distance Tests

Limited data are available on the braking distances achieved by different truck types under controlled field tests. Radlinski and Williams (7) provide braking distance data from 100 km/h for a range of truck types under both loaded and empty conditions on dry pavements. Figure 64 provides a comparison of the braking distance field data with those calculated in this study for a speed of 100 km/h and coeffcients of friction of 0.6 and 0.8, which are representative of dry pavements in excellent condition. It should be recalled that the vehicles analysed in this study are equipped with brake system characteristics reported by Radlinski and Williams. The diagram illustrates that there is reasonably good agreement between the two sets of results. Perhaps more important with respect to the objectives of this study is that both sets of results follow

the same trend. Loaded straight trucks have marginally longer braking distances than the semi-trailer and unloading of the vehicles degrades their braking characteristics. Bobtail tractors exhibit the poorest braking performance. A comprehensive evaluation of the capabilities of the braking models would require a systematic set of data on the braking capabilities of the different truck types on a range of pavement surface conditions. These could then be compared with the theoretical results.

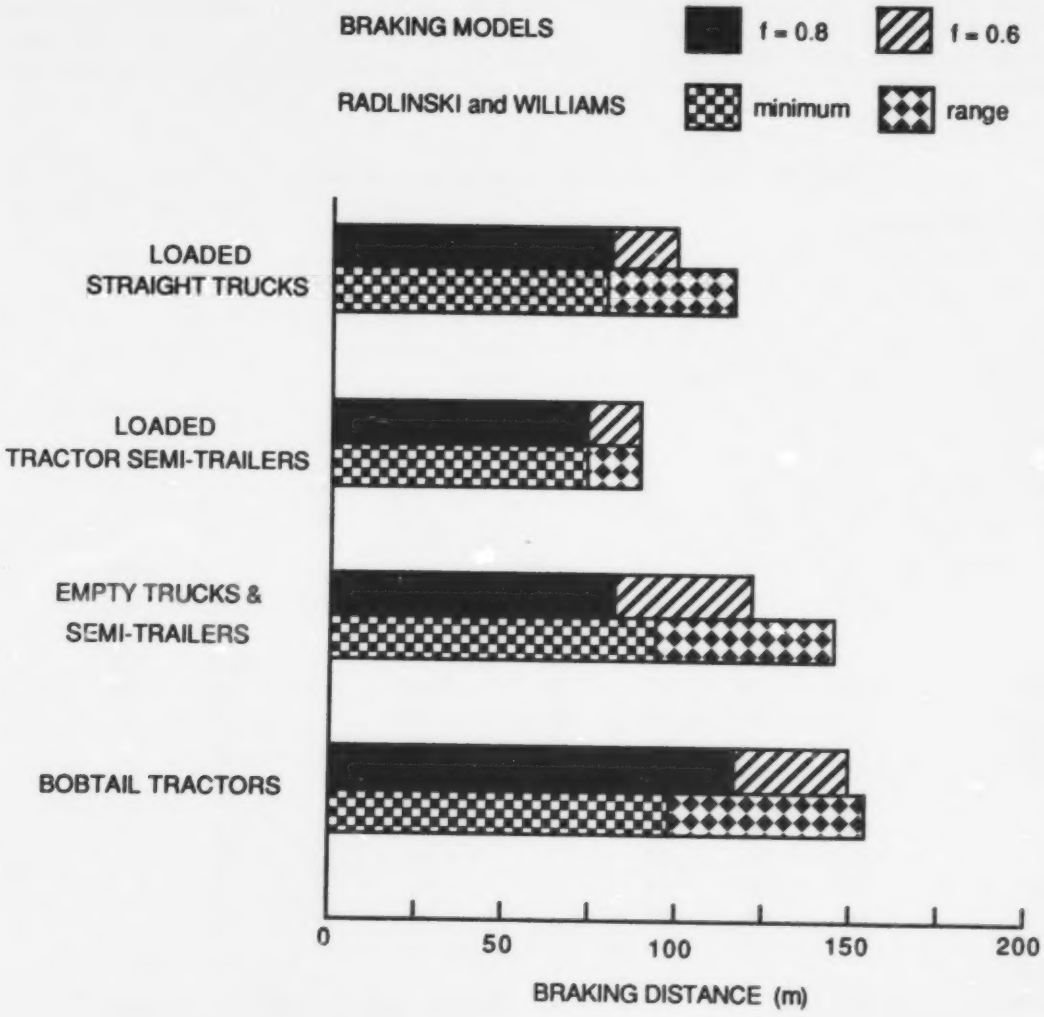


Figure 64. Comparison of Observed and Estimated Braking Distances for Different Trucks and Loading Conditions

CHAPTER 9

BRAKING EFFICIENCY SUMMARY FOR DIFFERENT TRUCK TYPES

The purpose of this chapter is to compare the braking efficiencies of the various heavy trucks and combination vehicles calculated in previous chapters. Table 16 summarizes the variations in the braking efficiencies with the mass, dimension, and brake system characteristics assumed for this study. The comparison is made across all vehicle types, the load conditions tested, an approach speed of 80 km/h, and tire-road friction coefficients of 0.2 and 0.6, representative of poor and good road conditions.

Table 16. Truck Braking Efficiencies from 80 km/h

entries are percentages

	Coefficient of friction							
	0.2				0.6			
Truck Types	Load Conditions				Load Conditions			
	FL	HL	U		FL	HL	U	
2-axle	90	78	81		63	61	70	
3-axle	81	82	67		70	68	65	
	FL	HL	U	BT	FL	HL	U	BT
3-S2	67	41	35	46	74	45	46	44
	FL/D	FL/U	HL/U	U/U	FL/D	FL/U	HL/U	U/U
3-S3/1B	76	78	80	61	82	74	84	65
3-S4/1B	79	68	55	35	77	64	65	35
3-S4/2B	76	92	89	53	72	63	86	57
3-S5/2B	55	70	58	37	55	63	65	38
	BF	RE	BE		BF	RE	BE	
3-S1-2	61	24	47		54	24	46	
3-S2-S2	71	25	47		69	25	47	
3-S3-S2	80	25	49		75	25	49	

Load Conditions:
- FL- Fully loaded to the legal limit
- HL- Half unloaded from the fully loaded condition
- U- Unloaded
- BT-Bobtail tractor
- /D-Belly axles down
- /U-Belly axles up
- BF- Both trailers fully loaded to the legal limit
- RE-Rear trailer unloaded with the front trailer remaining fully loaded
- BE-Both trailers unloaded

Figure 65 illustrates the braking efficiencies for the various truck types for a tire-pavement coefficient of friction of 0.2. The wide variations in braking efficiencies with changes in loading condition are clearly illustrated by the diagram. The double trailer combinations have the largest range of braking efficien-

cies ranging from about 25 percent for the cases with the rear trailer empty to about 70 percent for the fully loaded condition.

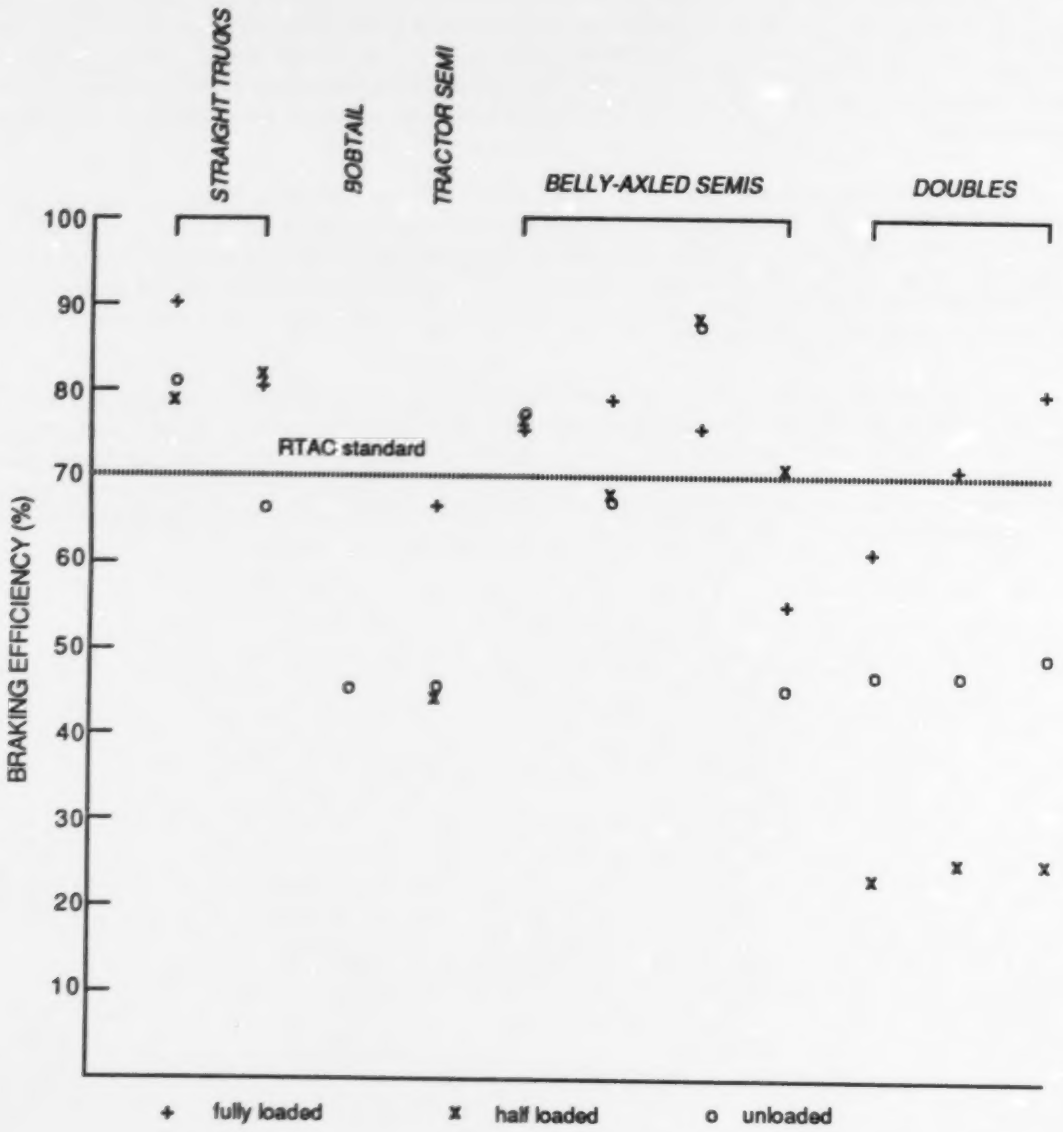


Figure 65. Variation in Braking Efficiency between Truck Types for Different Loading Conditions on Poor Pavements

It has been previously noted that the RTAC braking distances do not take into account the idea that deceleration should be limited to that dictated by the first axle that undergoes premature lockup in order to achieve a controlled stop. That is, the approach assumes that all vehicles have ideal braking. While this assumption may be reasonable for cars (although still overestimating braking capability) it is apparent from Table 16 that this assumption is not realistic for heavy trucks and combination vehicles.

It should be recalled that the RTAC proposed draft weight and dimension regulations suggest a minimum acceptable braking efficiency of 70 percent under any conditions of loading and tire-pavement friction. Table 16 emphasizes the connection between poor braking efficiency and poor braking performance. Note in particular the braking efficiencies of less than 50 percent exhibited by the unloaded 3-S4/1B and 3-S5/2B with belly axle(s) raised, 3-S2 vehicles which are not fully loaded, bobtail tractors, and double trailer combinations in which both trailers are not fully loaded. Inspection of the braking efficiencies summarized in Table16 indicates that most of the fully loaded truck configurations are capable of achieving the proposed standard.

The application of the same braking efficiency criterion to all coefficients of friction may not be appropriate. In the case of the 2-axle straight truck at a coefficient of friction of 0.2, even the relatively high braking efficiencies of well over the 70 percent criterion are insufficient to achieve braking distances within the design standards. As has been noted in Chapter 8, it is not possible for any vehicle to achieve the design standards even with ideal braking, at any coefficient of friction below 0.31 because the RTAC standards are based on this level of friction.

At a coefficient of friction of 0.6, the 2-axle straight truck is able to achieve the braking distance standard, even though its braking efficiencies are less than the 70 percent criterion. The extra friction above the 0.31 used in the braking distance standard calculation has compensated for the less than ideal braking. The application of one efficiency criterion to braking at all levels of friction can give a misleading impression of the extent to which the braking distance standard will be achieved. This is attributable to the braking distance standard being calculated using only one friction level and perfect braking efficiency.

CHAPTER 10

CLEARANCE TIMES SUMMARY FOR DIFFERENT TRUCK TYPES

It has been pointed out in Chapter 1 that each vehicle approaching a signalized intersection must receive a warning of an impending signal phase change of sufficient duration to avoid it being caught in a position where it can neither stop in time, nor clear the intersection. If the beginning of the amber interval places a vehicle in such a position, the driver is in a dilemma zone and cannot travel through the intersection without either increasing speed or violating the signal. The length of clearance interval (amber plus all-red) required to prevent the possibility of a particular vehicle finding itself in a dilemma zone depends on (i) the brake reaction time of a driver, (ii) the braking distance, (iii) the time for the front of a vehicle to cross an intersection, and (iv) the time for an entire vehicle to pass a point in an intersection.

Table 17 summarizes the required clearance times for all vehicles and load conditions with an approach speed of 80 km/h and coefficients of friction of 0.2 and 0.6. Table 17 also includes the required clearance times calculated using the ITE assumption that all vehicles are capable of performing a controlled stop at a deceleration of 0.31g.

Table 17. Required Clearance Times from 80 km/h

entries are in seconds

	Coefficient of friction								
	0.2				0.6				
Truck Types	Load Conditions				Load Conditions				ITE
	FL	HL	U		FL	HL	U		
2-axle	8.2	9.1	8.8		4.9	5.0	4.6		5.5
3-axle	8.9	8.9	10.4		4.6	4.7	4.8		5.6
	FL	HL	U	BT	FL	HL	U	BT	
3-S2	11.0	16.3	18.6	14.3	5.1	6.7	6.6	6.3	6.2
	FL/D	FL/U	HL/U	U/U	FL/D	FL/U	HL/U	U/U	
3-S3/1B	9.8	9.6	9.4	11.7	4.7	4.9	4.6	5.2	6.0
3-S4/1B	9.7	10.8	12.7	18.8	5.0	5.5	5.4	7.9	6.2
3-S4/2B	9.9	8.7	8.9	13.2	5.1	5.5	4.7	5.9	6.2
3-S5/2B	12.9	10.6	12.3	17.9	5.9	5.5	5.4	7.5	6.2
	BF	RE	BE		BF	RE	BE		
3-S1-2	11.9	26.6	14.8		6.1	10.7	6.7		6.3
3-S2-S2	10.7	25.1	14.7		5.4	10.2	6.7		6.3
3-S3-S2	9.7	25.6	14.2		5.2	10.3	6.5		6.3

It has been pointed out in Chapter 1 that the Institute of Transportation Engineers recommends that

the braking distance required for the calculation of the clearance time be based on a deceleration of 0.31g. It is assumed that drivers will choose not to exceed this rate, except in emergency situations, because it is the maximum rate considered to be comfortable. The ITE standard also assumes, however, that the braking efficiency of a vehicle will not limit the deceleration to an even lower level.

10.1 Loaded Vehicles

Figure 66 illustrates the signal clearance times required by the loaded vehicles for coefficients of friction of 0.2 and 0.6. The diagram illustrates that all vehicle types are capable of achieving the ITE standard at a coefficient of tire-pavement friction of 0.6.

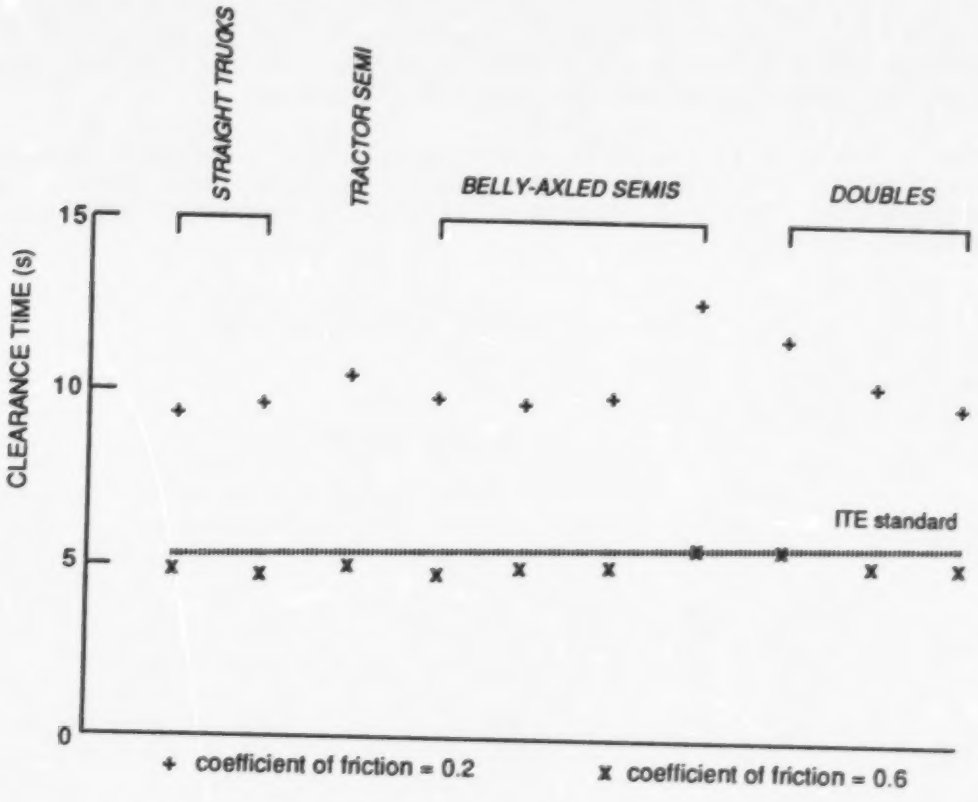


Figure 66. Clearance Times Required by Fully Loaded Vehicles

The diagram illustrates the increases in clearance times required by the various vehicle types under very poor pavement conditions. Their inability to meet the ITE standard is not surprising, since even with perfect braking efficiency the maximum deceleration that could be achieved would be 0.2 g.

10.2 Half Loaded Vehicles

Figure 67 shows the clearance times required by the half loaded vehicles for the two coefficients of tire-pavement friction. The diagram illustrates that all of the vehicles types, other than the double trailer combinations are capable of achieving the ITE standard under the dry pavement conditions. The double

trailer combinations with rear trailers empty require clearance times of almost double the ITE standard even under the dry pavement conditions. The poor braking behaviour of the half loaded tractor semi-trailer and the double trailers under the poor pavement conditions is reflected in the long clearance times illustrated in Figure 67.

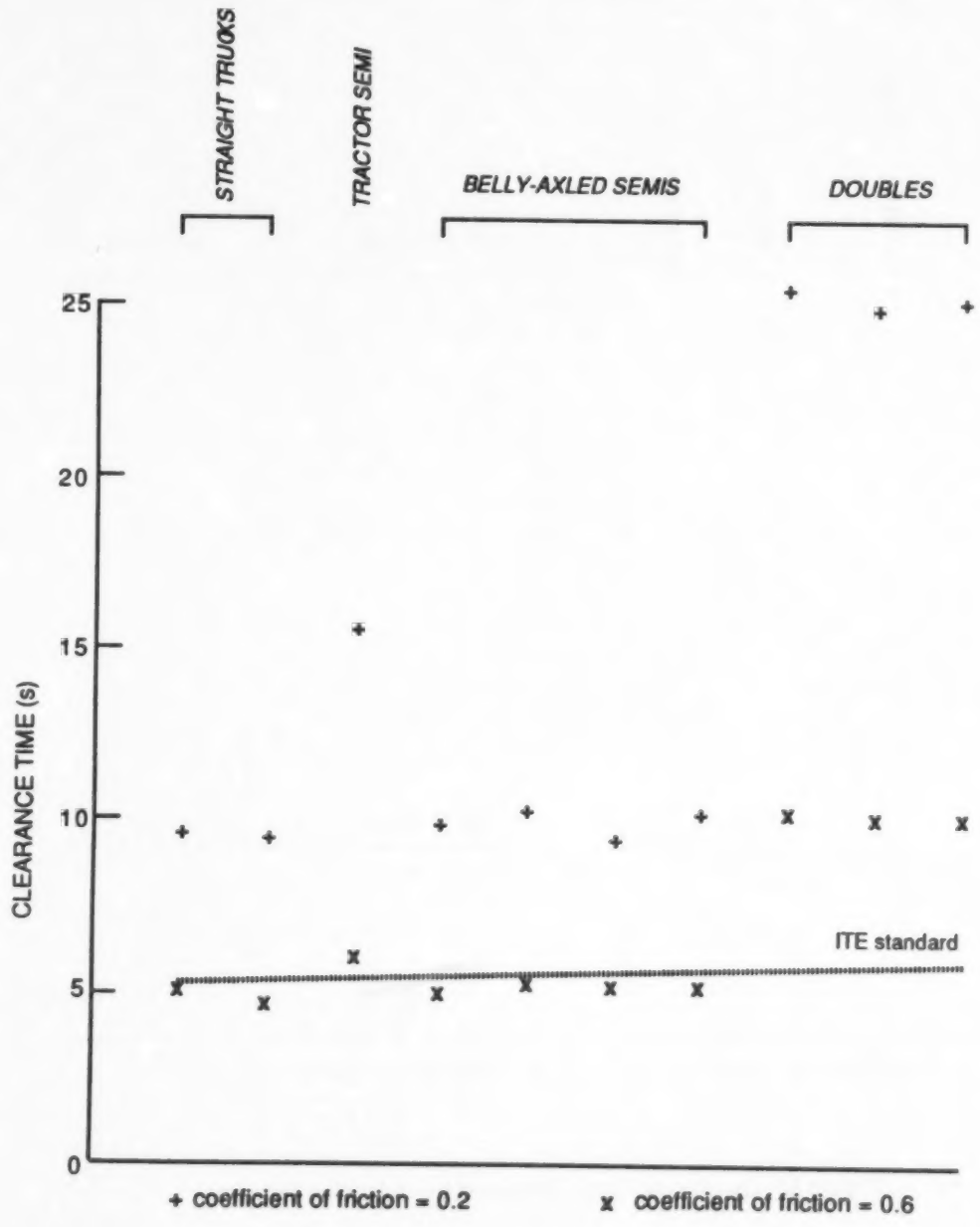


Figure 67. Clearance Times Required by Half Loaded Vehicles

10.3 Unloaded Vehicles

Figure 68 shows the clearance times required by unloaded vehicles. The poor braking characteristics of the bobtail tractor, tractor semi-trailer and double trailer vehicles are reflected in their large required clearance times under poor pavement surface conditions.

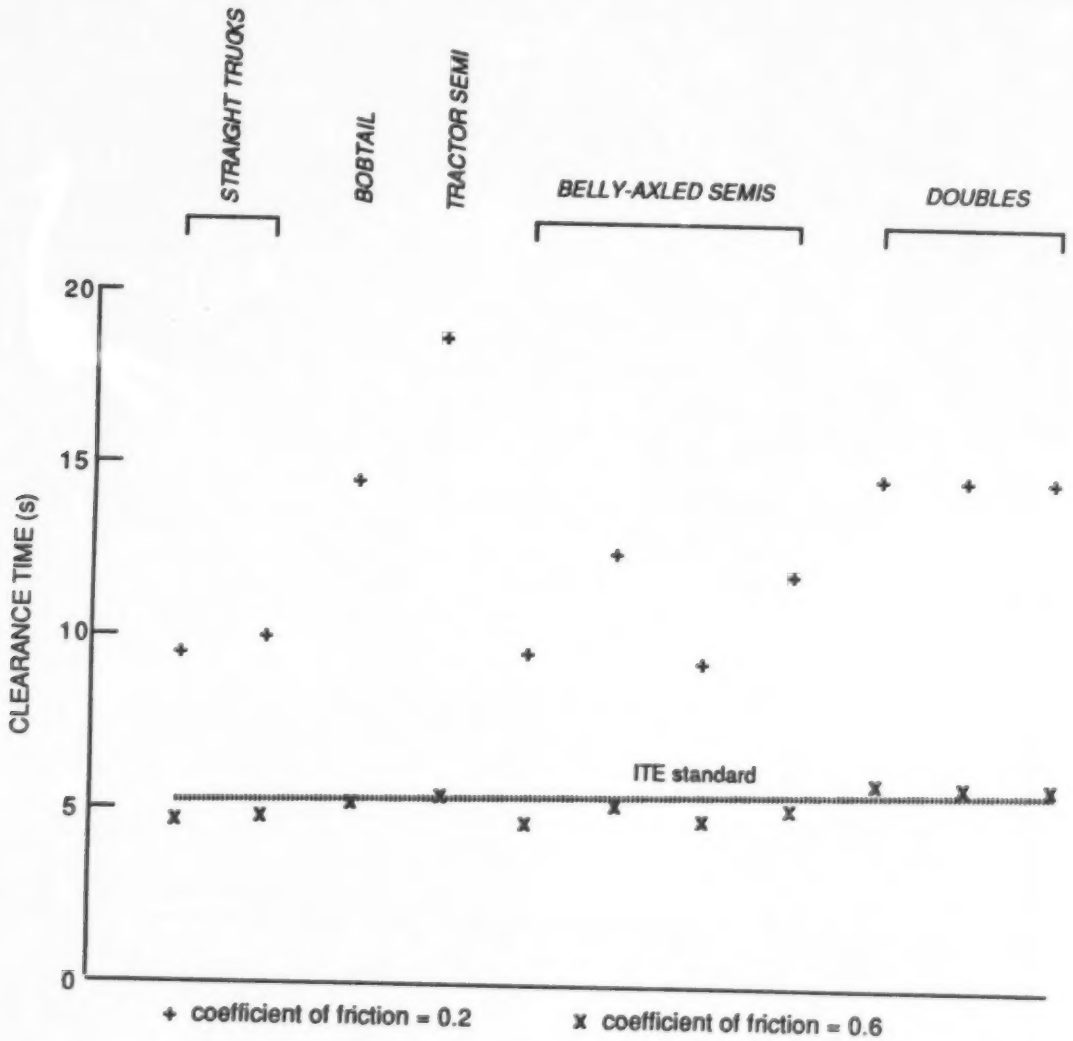


Figure 68. Clearance Times Required by Unloaded Vehicles

CHAPTER 11

ANALYSIS OF TRUCK ACCIDENT DATABASE

11.1 Accident Rates for the Provincial Highway System

Buyco, Saccomanno and Stewart (11) have conducted a comprehensive analysis of the 1983 MTC truck accident data base. The 1983 data base was selected because it could be supplemented with truck exposure information derived from the 1983 MTC Commercial Vehicle Survey (12). Table 8 summarizes the accident rates by truck type calculated by Buyco, Saccomanno and Stewart.

Table 18. Accident Rates per Million Vehicle Kilometres

Truck Type	Accident Rate
Empty Straight Truck	2.62
Bobtail Tractor	1.74
Empty Tractor-Trailer	1.32
Loaded Straight Truck	1.27
Loaded Tractor-Twin Trailer	0.75
Loaded Tractor Trailer	0.58
Unloaded Tractor-Twin Trailer	0.51

Inspection of the entries in Table 18 reflect in a general way some of the findings of this study. Except for the twin trailers, the highest accident rates were for unloaded straight trucks and semi-trailers and bobtail tractors. It must be recognized that the accident rates in Table 18 are for all accident causes and not just braking related accidents. It is not possible to assess the extent to which the changing braking capabilities of the different truck designs contributed to the variations in observed accident rates. However, this very macroscopic comparison would suggest the need for a systematic analysis of braking-related accidents.

11.2 Accidents at Signalized Intersections

The accident database assembled for the above-mentioned study was sorted so that only those records for which the traffic control was reported as an operating traffic signal and the vehicle maneuver was recorded as stopping/slowing were retained and the number of fields was reduced to twelve.

Two of these fields were traffic control (TRACON) and vehicle maneuver (VEHMAN) which were used to filter the database mentioned above. Three fields were selected as being indicators of the type and severity of the accident and these are :

1. accident class (CLASAC) - fatal, injury, property damage, or non-reportable,
2. type of initial impact (INTIMP), and
3. total property damage (TOTDMG).

Seven fields were selected as variables which could be influencing the type and severity of truck accidents under braking at signalized intersections and these are:

1. visibility(VISIBI),
2. light conditions (LIGHT),
3. road surface conditions (RDSUR1),
4. road type (RDTYP1),
5. truck type (TRKTYP),
6. load condition (VEHLOD), and
7. vehicle condition (VEHCON), any mechanical defects noted by the reporting officer.

This reduced the number of accident records dramatically from 4377 records to just 52. Virtually all of the accidents in the records retained occurred during daylight on asphalt roads, so the tables resulting from crosstabulations with the variables LIGHT and RDTYP1 were neglected. For the variable TOTDMG, the values were grouped into ranges of damage values in dollars. For the variable TRKTYP, the variety of truck types recorded were grouped as 3-axle trucks, bobtail tractors, tractor semi-trailers, and tractor semi-trailers with an attached trailer. Three of the crosstabulation tables are presented in Tables 19, 20 and 21. In reviewing the entries in these tables it should be remembered that the accidents are limited to those which occurred at traffic signals under MTC jurisdiction.

Table 19 illustrates the accident type cross-classified by truck type and the entries show that rear-end accidents represent more than half the accidents. The table shows that accidents by three axle straight trucks and 3-S2 tractor semi-trailers dominate. This is not surprising since these truck classes represent the largest truck movement categories. While the bobtail tractor accidents are small in number they are over-represented in the sample given their relatively small usage.

Table 19. Truck Type versus Accident Type

Accident Type	Truck Type			
	3-Axle Truck	Bobtail	3-S2	Doubles
Rear End	12	1	12	2
Angle	3	2	6	0
Turning	3	0	1	0
Side Swipe	1	1	1	0
Single Vehicle	2	0	5	0
Total	21	4	25	2

Table 20 illustrates the accident type cross-classified by load condition. An interesting feature of the table is that the number of accidents is roughly equal for the loaded and unloaded conditions which suggests that unloaded trucks are over-represented in accidents at signalized intersections. This is consistent with the findings of Buyco et al (11) and Wolkowicz and Billing (13). It should also be noted that unloaded vehicles were involved in all of the single vehicle accidents where braking has been identified as the primary cause.

Table 21 illustrates the accident type cross-classified by road surface condition. The most imporatnt feature illustrated by Table 21 is that the bulk of the accidents occurred under dry conditions followed by accidents on wet pavements. This indicates that poor pavement conditions are strongly over-represented in the accidents at signalized intersections givent the split of vehicle usage that might be expected between dry, wet and slushy/icy conditions.

Table 20. Load Condition versus Accident Type

Accident Type	Load Condition		
	Unloaded	Loaded	Unknown
Rear End	7	17	3
Angle	6	5	0
Turning	1	0	3
Side Swipe	1	1	1
Single Vehicle	6	0	1
Total	21	23	8

Table21. Road Surface Condition versus Accident Type

Accident Type	Road Surface Condition		
	Dry	Wet	Slush/Ice
Rear End	16	10	1
Angle	6	3	2
Turning	0	4	0
Side Swipe	2	1	0
Single Vehicle	4	3	0
Total	28	21	3

11.3 Commercial Vehicle Accident Study

An important source of information on the causes of commercial vehicle accidents is provided by Wolkowicz and Billing (13) who provide detailed information on 140 accidents on highways in the Metropolitan Toronto area during the winters of 1979/1980 and 1981. Eighty-eight percent of the accidents recorded during the study period were attributed to the driver while 12 percent were caused by mechanical failure.

Table 22 summarizes the causes of loss of control accidents observed in the study for all truck types, where braking is normally an important factor. Inspection of the table entries show that they are consistent with the evidence introduced in the previous sections of this chapter. If one assumes that rollover accidents are not initiated by braking, then empty trucks had about 5.5 times more accidents than fully loaded trucks. This is consistent with the previous evidence as well as the information on the changing braking capabilities of trucks under different load and pavement skid resistance conditions. Wolkowicz and Billing (13) note :

> *"Directional control loss, skidding, jackknifing, and trailer swing are all most often caused by loss of traction at one or more tire sets. This is more likely, of course, on wet and icy surfaces which have reduced tire/road friction capability. In many cases, the loss of traction is due to braking, and braking is more likely to lock the wheels of an empty or lightly loaded vehicle, for which brakes are generally oversized, than on a CV with a full load. Locked wheels destabilize a vehicle and (often catastrophically) reduce its controllability, making an accident more probable."*

Table 22. Causes of Loss of Control Truck Accidents

	Load			Surface		
	Empty	Full	Unk.	Dry	Wet	Slush/Ice
loss of directional control	10	4	1	8	4	3
skid	20	3	2	5	10	9
jackknife	21	2	4	1	19	10
trailer swing	2	1	0	0	1	2
rollover	5	17	0	17	4	1
Total	61	27	6	31	38	25

The table entries emphasize the relatively high frequency of jackknife accidents with empty vehicles operating on wet and slushy/icy pavements. This instability is created by lockup of tractor drive axles and these axles are typically overbraked in the unloaded condition. It is also interesting to note that empty trucks dominate the skidding accidents as well as those involving loss of directional control.

While it is very dangerous to generalize from this very superficial review of truck accident analyses in Ontario, the accident experience is certainly consistent with many of the theoretical results outlined in this report. It seems clear that more systematic evidence needs to be be assembled on the braking related causes of accidents and correlated to the types of braking performance suggested by the theoretical models.

CHAPTER 12

CONCLUSIONS

Current braking distance standards used for traffic signal timing decisions and geometric design of highway alignments are based on a coefficient of tire-pavement friction magnitude of about 0.3 which is representative of worn tires operating on wet pavements. Braking distance standards assume that vehicles possess perfect braking efficiencies and this means that vehicles can achieve a deceleration of about 0.3 g.

The braking capabilities of the different truck types analysed in this report are expressed in terms of three inter-related performance measures and these are braking efficiency, braking distance and inter-phase clearance times at traffic signals. Perfect braking efficiency means that the available tire-pavement friction is fully mobilized and that trucks brake in a minimum distance from a given speed for the prevailing roadway conditions. The analyses described in this report have illustrated that the braking capabilities of trucks vary widely between truck types, with load conditions and with pavement skid resistance.

Analyses of the braking distances required by fully loaded trucks demonstrate that tire-pavement friction magnitudes of from 0.5 to 0.8 (magnitudes which reflect very good tire-pavement friction) are required for trucks to achieve current braking distance standards. Braking distances increase significantly when trucks are partially loaded or unloaded, where the magnitude of this degradation in braking capabilities depends on the truck type. The longest braking distances are required by partially loaded trucks, particularly those unloaded from the rear. Tractor semi-trailers, belly-axled semi-trailers with tridem rear axle groups and double trailer combinations with unloaded rear trailers require very long braking distances, particularly under poor pavement skid resistance conditions.

These changes in braking distances reflect the changing braking efficiencies of trucks with fixed brake systems which have to operate under changing load and pavement conditions. Most of the truck types tested exhibit braking efficiencies close to the proposed 70 percent braking efficiency standard when fully loaded. The principal exceptions are belly-axled semi-trailers with tridem rear axle group (53% braking efficiency) and the A-train double (54-61%).

The braking efficiencies of some of the vehicles decreased sharply under partial loading with the largest reductions occurring for tractor semi-trailer half unloaded from the rear (41-45%), and the A- and B-train doubles with rear trailers empty (25%). The partially loaded condition produces lower braking efficiencies than the unloaded condition for most of the vehicle types. Exceptions to this are the belly-axled semi-trailers with tridem rear axles which exhibit braking efficiencies of about 35% in the unloaded condition with belly axles raised.

The Institute of Transportation Engineers standards for signal clearance times can only be achieved by most truck types when the coefficient of tire-pavement friction is in the range of 0.5 to 0.6. Poorer pavement conditions produce important increases in the required signal clearance times, where the increases reflect the greater than average degradation in braking efficiencies of many of the truck types. Bobtail tractors, tractor semi-trailers and some of the partially loaded and unloaded belly-axled semi-trailers and double trailers operating under poor pavement conditions require clearance times two to four times longer than those suggested by the standards.

The results presented in this report must be interpreted carefully. The braking capabilities of trucks have been estimated from simplified braking models using truck mass, dimension and brake properties obtained from a variety of sources. While the very limited field test data available suggest that the models are capable of capturing the braking behaviour of trucks, additional comparisons of model predicted and observed braking behaviour are required.

Several analyses of truck accidents in Ontario provide evidence that is compatible with the theoretical trucking behaviour described in this report. Unloaded trucks are strongly over-represented in loss of control accidents and many of the accidents investigated in detail showed that the primary cause of the accidents was the premature lockup of critical axle groups during braking. It is not possible to develop direct cause and effect linkages between the braking behaviour described in this report and specific-braking related accidents because of the unavailability of detailed weight, dimension and brake information for particular trucks.

The evidence assembled in this study indicates that many of the braking distance-related engineering standards used for highway design and management need to be carefully reviewed. Current geometric design standards are based on the braking capabilities of cars and it is assumed that the much larger driver eye heights of truck drivers compensates adequately for their longer braking distances. While this assumption may be valid for many highway design situations, it is an assumtpion that must be carefully evaluated in site distance-constrained situations.

The provision of longer clearance times at signalized intersections is likely to create some difficulties. Increased clearance times may exacerbate signal compliance problems at signalized intersections if drivers use the additional time to accelerate through the intersection rather than to brake comfortably to a stop. Increased clearance times reduce intersection capacity and the evidence on clearance time requirements presented in this report will have to be carefully integrated with information on the capacity impacts of trucks in order to optimize the overall performance of signalized intersections that carry significant truck volumes.

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